PILE FOUNDATIONS

By

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Preface

Pile foundations is a very vast subject and it is not possible to cover all the information regarding pile foundations in one book or presentation. The objective of this presentation is to give an overall view of the subject which will serve as beginners guide. The focus of the presentation is mainly on onshore pile foundations. The author has tried to explain the subject through simple concepts and visuals without giving detailed methodologies or mathematical concepts to maintain the interest of the beginner ,without loading his mind with unnecessary confusion . However, some formulae were presented at some places only to appreciate the statements made. The author assumes that the reader has basic knowledge of soil mechanics and foundation engineering and basic principles of engineering. The author will be pleased to accept comments and suggestions, without deviating from the basic objective of the presentation, for further improvement.

Varanasi Rama Rao

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1.GENERAL

Overview

Pile foundations are adopted generally in the following situations:

- Low Bearing Capacity of soil .

- Non availability of proper bearing stratum at shallow depths.

- Heavy loads from the super structure for which shallow foundation may not be economical or feasible.

Classification of Piles

- Based on material
  - Concrete
  - Steel
  - Timber
- Based on method of construction/installation.
  - Driven /Displacement Pre cast Piles
  - Driven/Displacement Cast in Situ Piles
  - Bored/ Replacement Pre cast piles
  - Bored/ Replacement Cast in situ piles.
- Based on Load transfer mechanism
  - End bearing piles
  - Friction/Floating piles
  - Bearing cum Friction piles

- **Based on sectional area**
  - Circular
  - Square
  - H
  - Octagonal
  - Tubular
- **Based on Size**
  - Micro piles dia. < 150 mm
  - Small dia. pile dia. >150mm and <600 mm
  - Large dia. piles > 600 mm
- **Based on inclination**
  - Vertical Piles
  - Inclined/ raker Piles

How does a pile look like?

- Before presenting the actual picture of a pile foundation **some** schematic pictures of pile foundation are presented below.

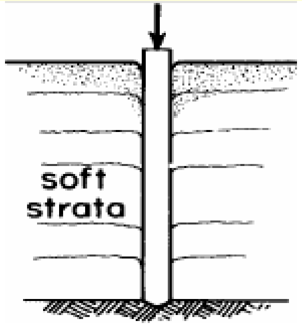


Fig.1: Point Bearing Files

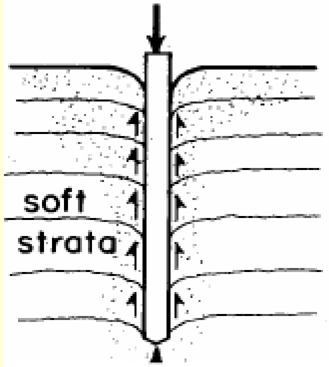


Fig.2: Friction Piles

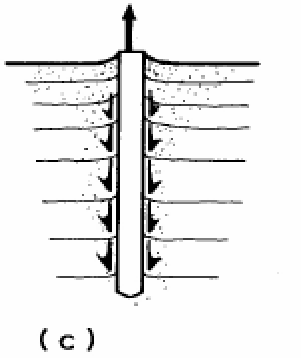


Fig.3: Uplift Piles

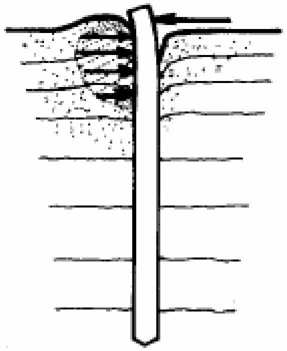


Fig.4

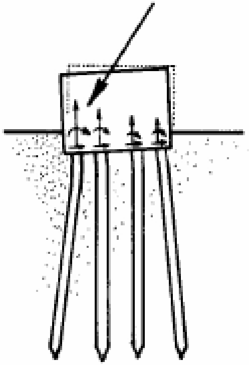


Fig.5

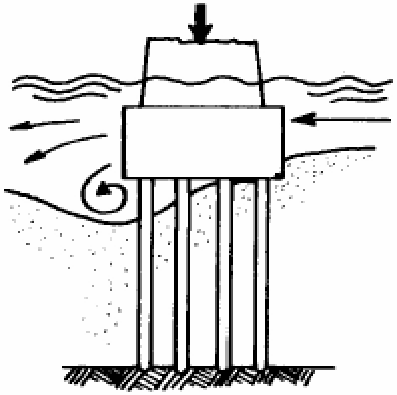


Fig.6

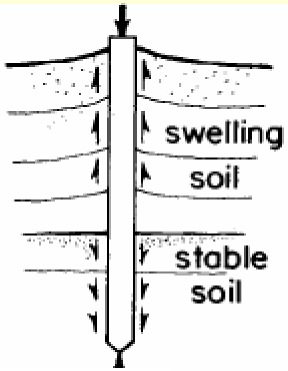
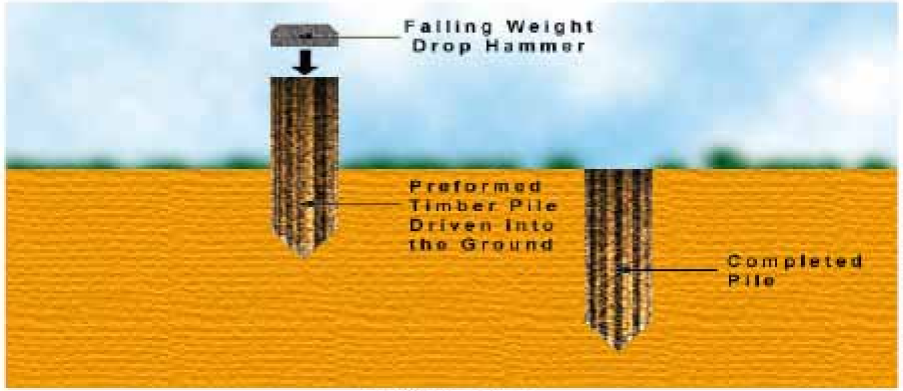


Fig.7

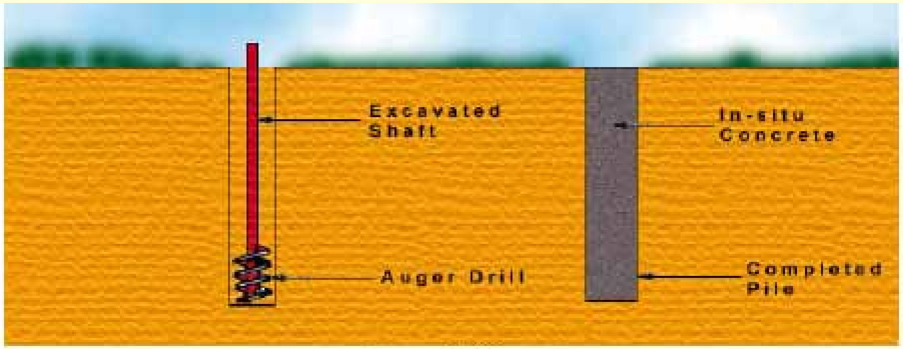
Figure 1

All the above schematics show the various types of pile foundations and loads carried by them

Schematics of Pile foundations based on method of construction



Driven Piles



Bored Piling

Figure 2

What are the loads coming on to the pile foundation?

- All the loads from super structure viz. Dead loads, Live loads Wind loads and Seismic loads.
- The loads from the surrounding soil in case of seismic event.
- Water loads in the case of off- shore structures

Typical loading diagram on a single pile embedded in soil

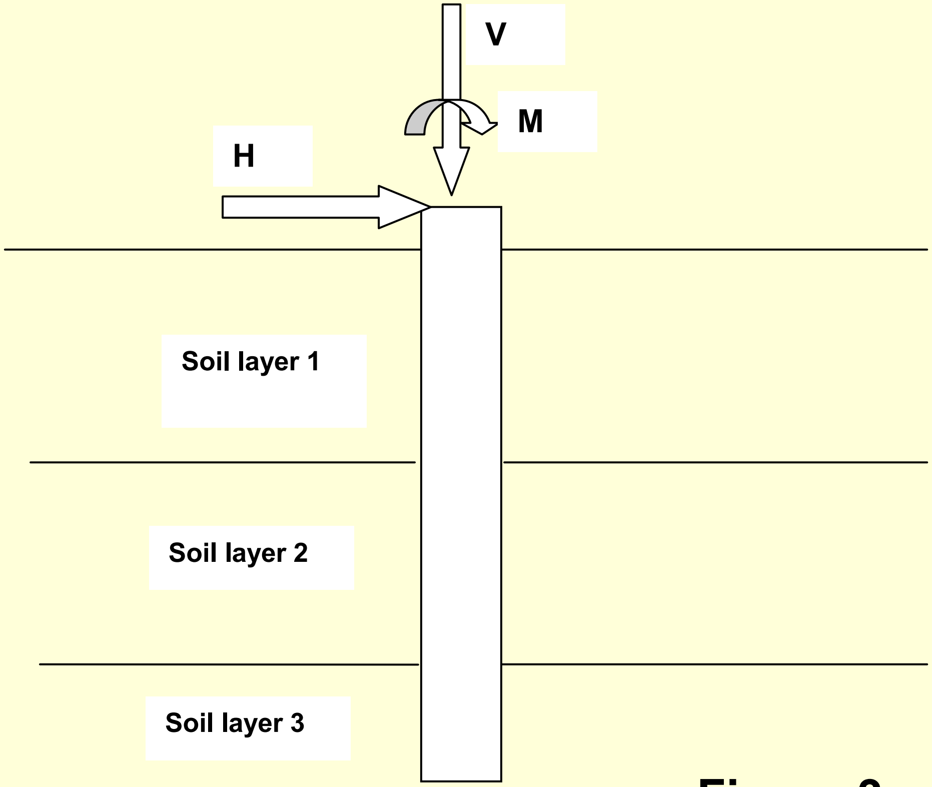


Figure 3

Note: V can be either downward or upward depending on the pile is subjected to compressive or tensile load

Piles usually exist as groups which are all integrated by means of a pile cap as shown in the below schematic

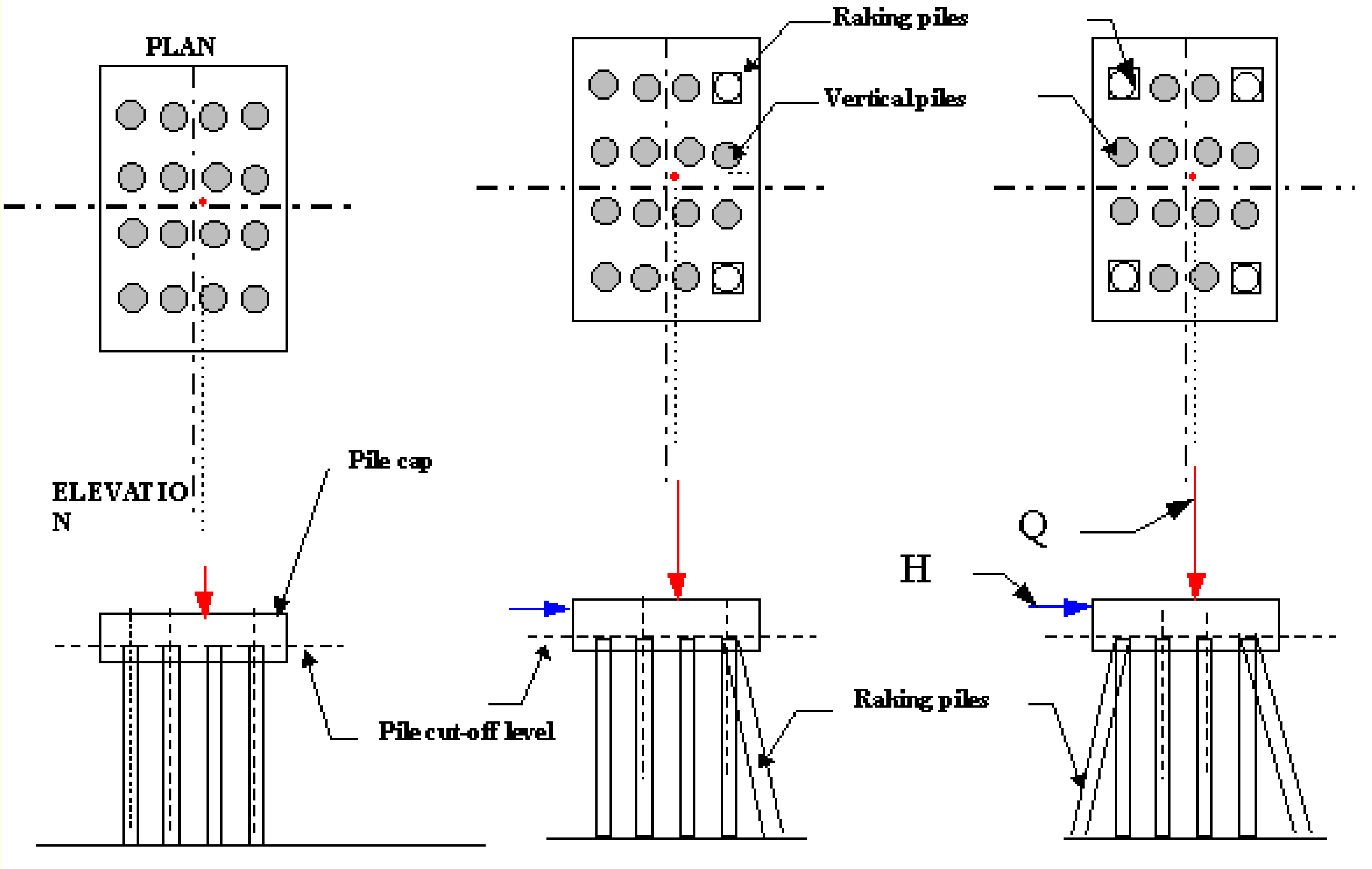


Figure 4

What are the load carrying mechanisms of piles?

- End bearing cum friction piles carry vertical compressive loads partly by means of resistance offered by the hard stratum at the tip of the pile and partly by the friction developed between the pile shaft and soil

- Pure friction piles carry the major part of loads only by means of friction developed between pile shaft and soil; and pure End bearing piles only by means of bearing resistance at the tip of the pile

- In both the above cases lateral loads are carried by the lateral resistance offered by the surrounding soil.

SCHEMATICS SHOWING AXIAL LOAD CARRYING MECHANISM

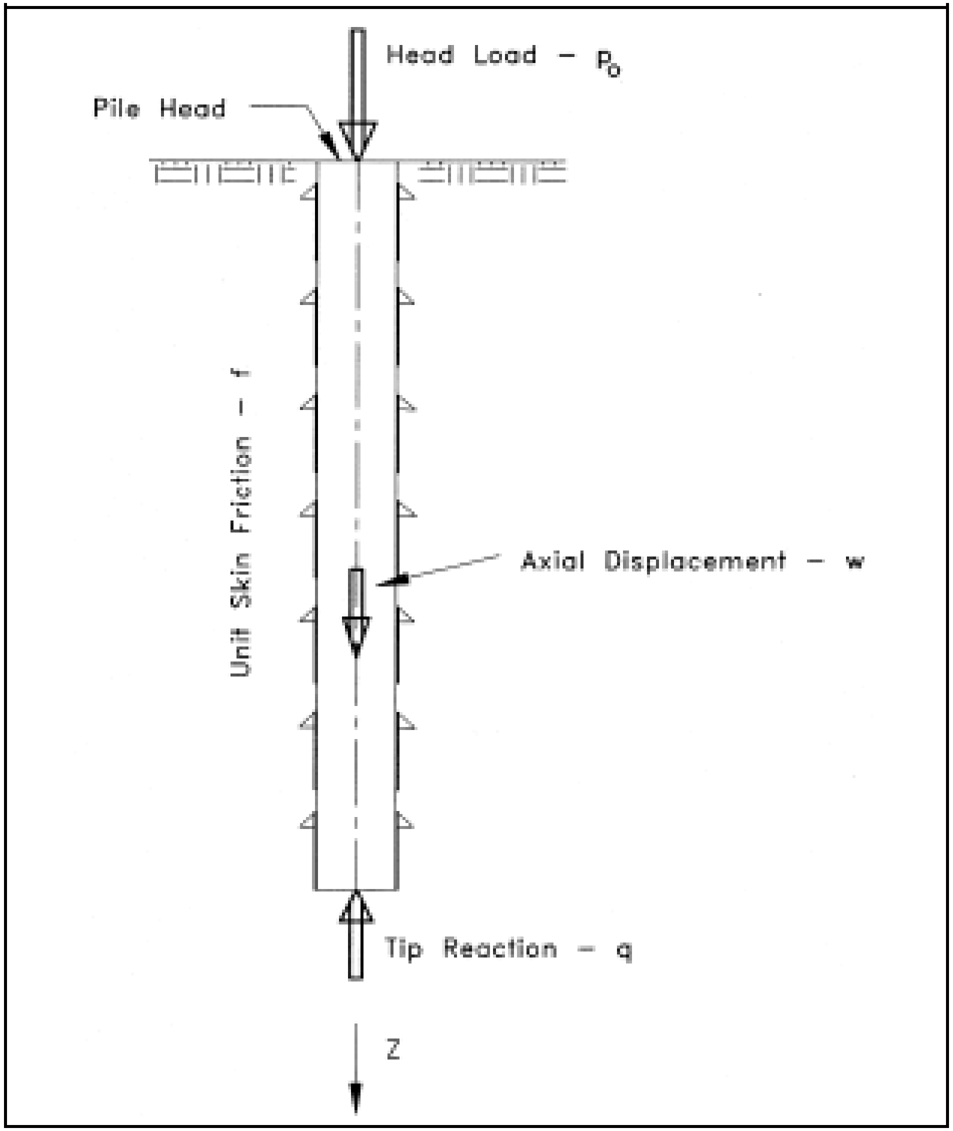
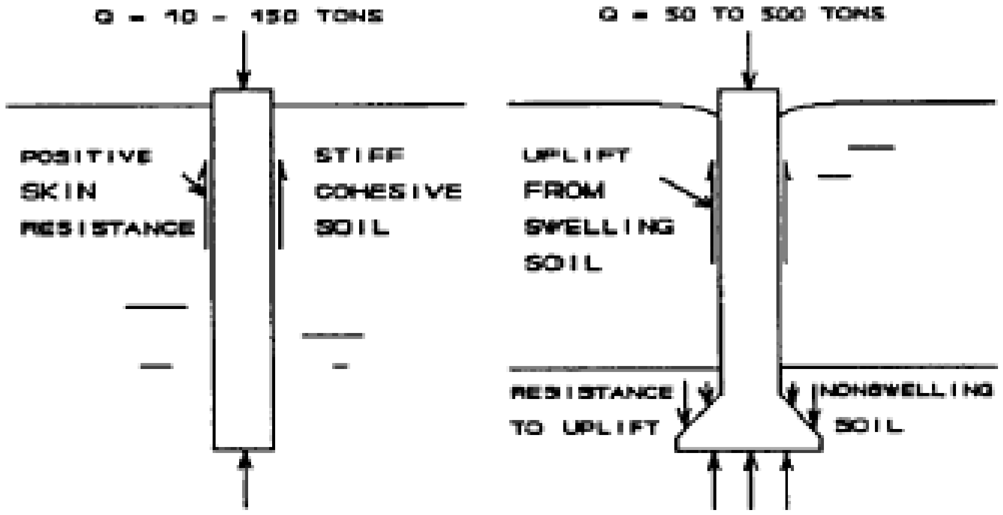
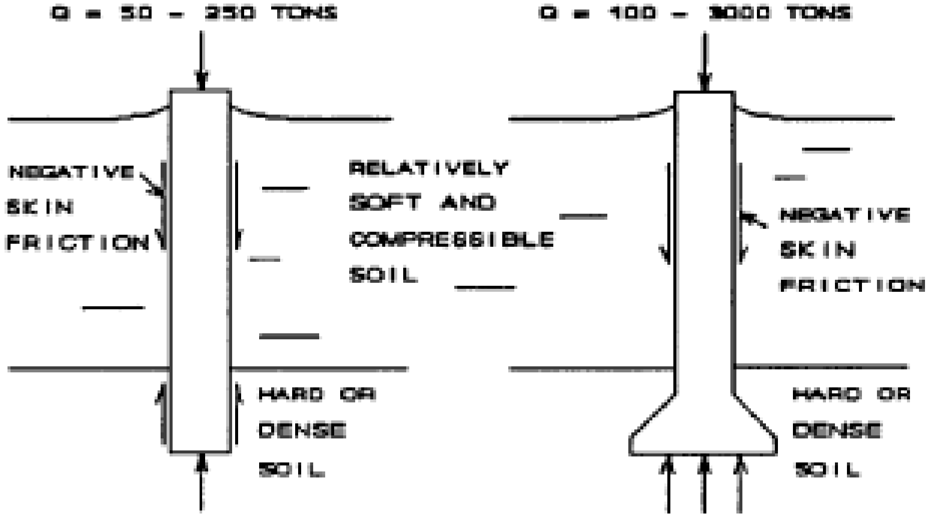


Figure 1. Axially loaded pile

Figure 5



a. FLOATING SHAFTS IN HOMOGENENOUS SOIL



b. SHAFTS END BEARING IN HARD SOIL

Figure 6

Load carrying mechanism of pile subjected to Lateral Loading and Moment

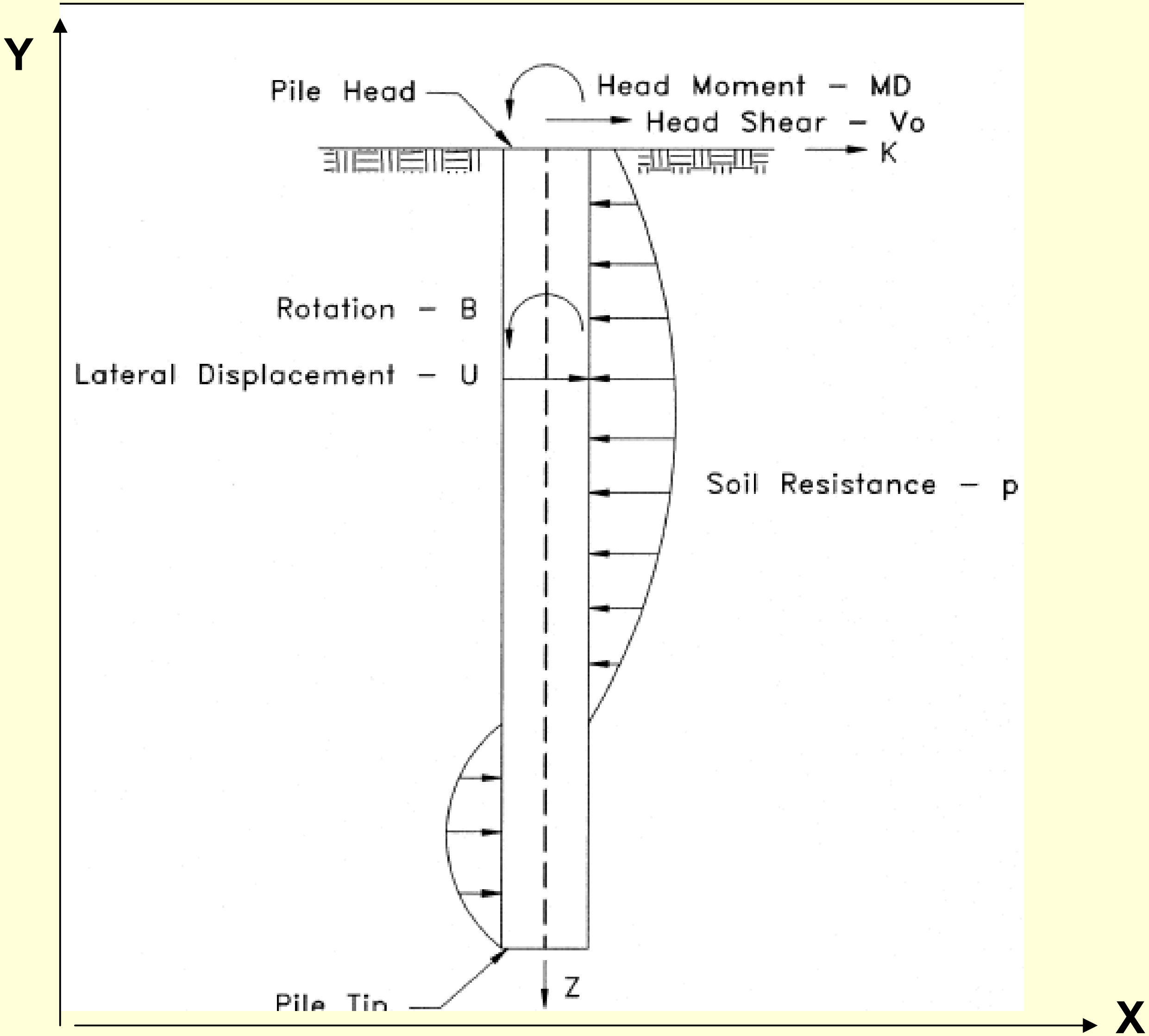
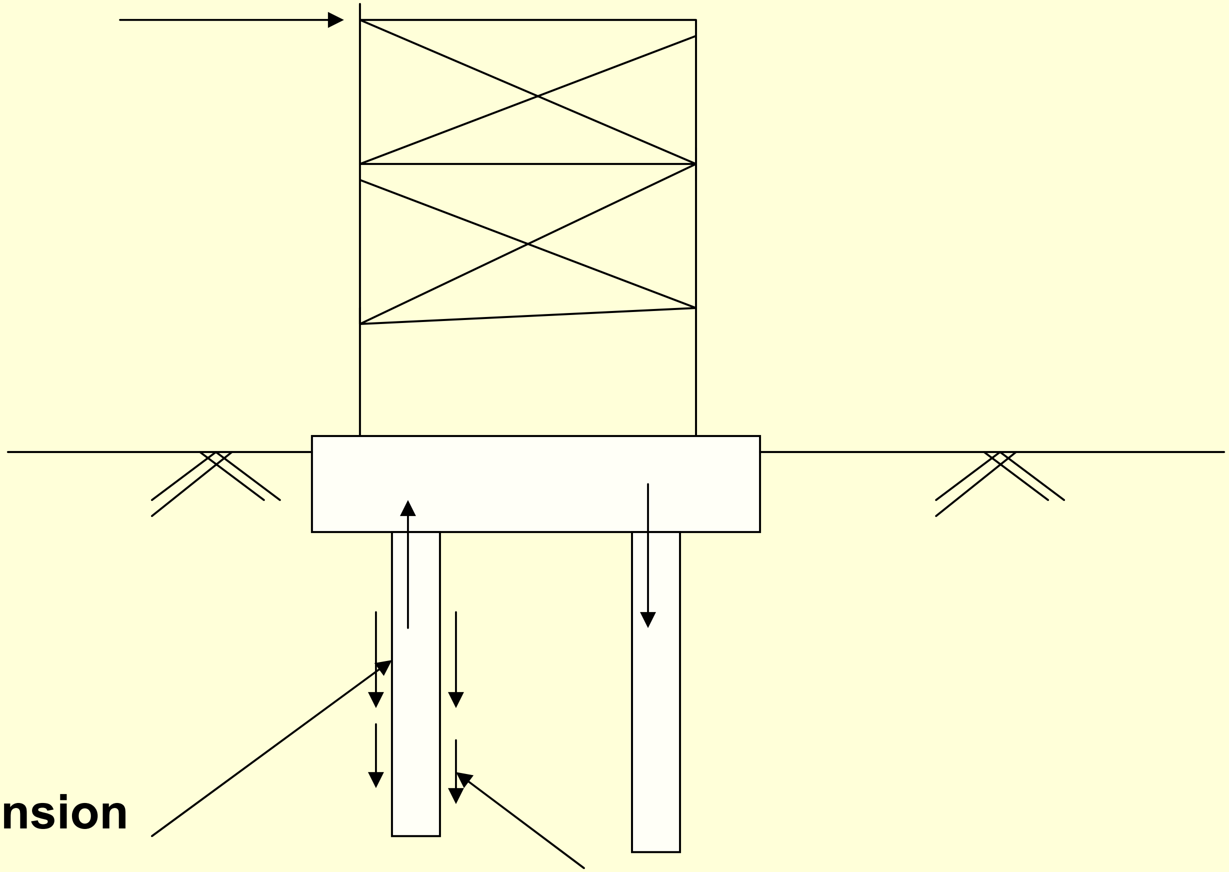


Figure 7

Load carrying mechanism of pile Subjected to tension/pullout



Pile in tension

Only friction and weight of pile will resist tension.

Figure 8

What is meant by load carrying capacity of the pile foundation?

Load carrying capacity of the pile in the context of foundation engineering:

The amount of load the pile can carry without undergoing continuous displacements for insignificant load increments by virtue of its boundary condition (soil condition) and not by virtue of its structural strength.

the assumption for this definition is – the failure of surrounding soil occurs prior to the failure of the pile material especially in the case of concrete piles

Pile Capacities

What are the various capacities of pile commonly used in practice?

- Axial capacity

- Lateral capacity

- Pullout capacity or Tension capacity

How to estimate the capacity of a Pile? What are the approaches?

The two approaches for obtaining capacity of the pile are

- Field approach

In this approach the pile is loaded to the desired level and its capacity is estimated.

- Theoretical Approach

In this approach the pile capacity is calculated using some formulae into which soil data is fed for obtaining the capacity.

Field Approach

A Test pile of required dimensions is constructed in the field and a load test is conducted to assess the capacity of the pile.

This approach gives more realistic estimate of pile capacity. However it is time consuming and costly

Load Tests On a Single Pile

The load tests are categorized as

Stress tests

- Maintained load test (Static vertical load test)
- Constant rate of penetration test
- Lateral load test
- Dynamic load test
- Cyclic load test (not discussed in this presentation)

Strain tests

- Low strain integrity testing
- High strain integrity testing.

Pile load tests are usually carried out for the following main reasons:

- To obtain back figured soil data that will enable other piles to be designed

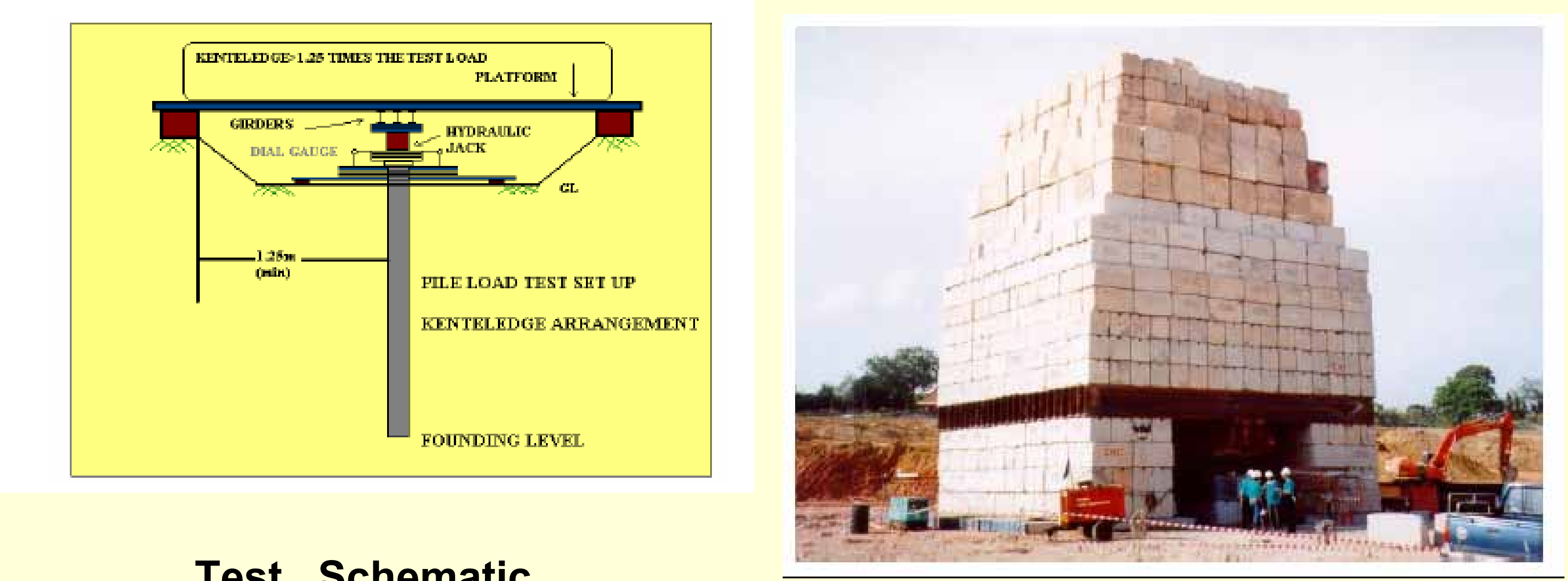
- To confirm pile lengths and hence contract costs before the client is committed to over all job costs

- To counter check results from geotechnical and pile driving formulae

- To determine the load-settlement behavior of the pile, especially in the region of anticipated working load, that the data can be used for prediction of group settlement.

- To verify the structural soundness of the pile.

Field setup for a Static Axial compressive load test on a single pile



Test Schematic

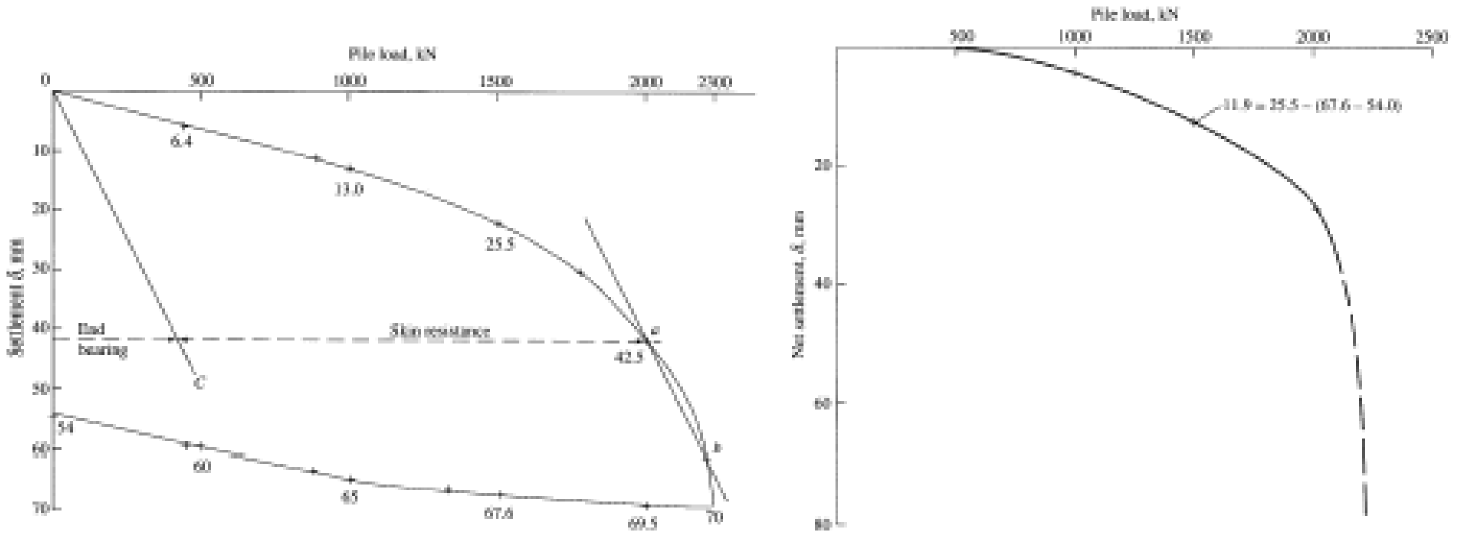
Real time field set up

Figure 9

Determination of pile axial compressive capacity from static load test

The Pile load test data is presented as shown below

Figure 10



(a) Usual method of presenting data.

(b) Plot of load vs. net settlement computed as shown on the figure using data from (a).

From the above plots the ultimate pile load is commonly taken as the load where the load settlement curve approaches a vertical asymptote

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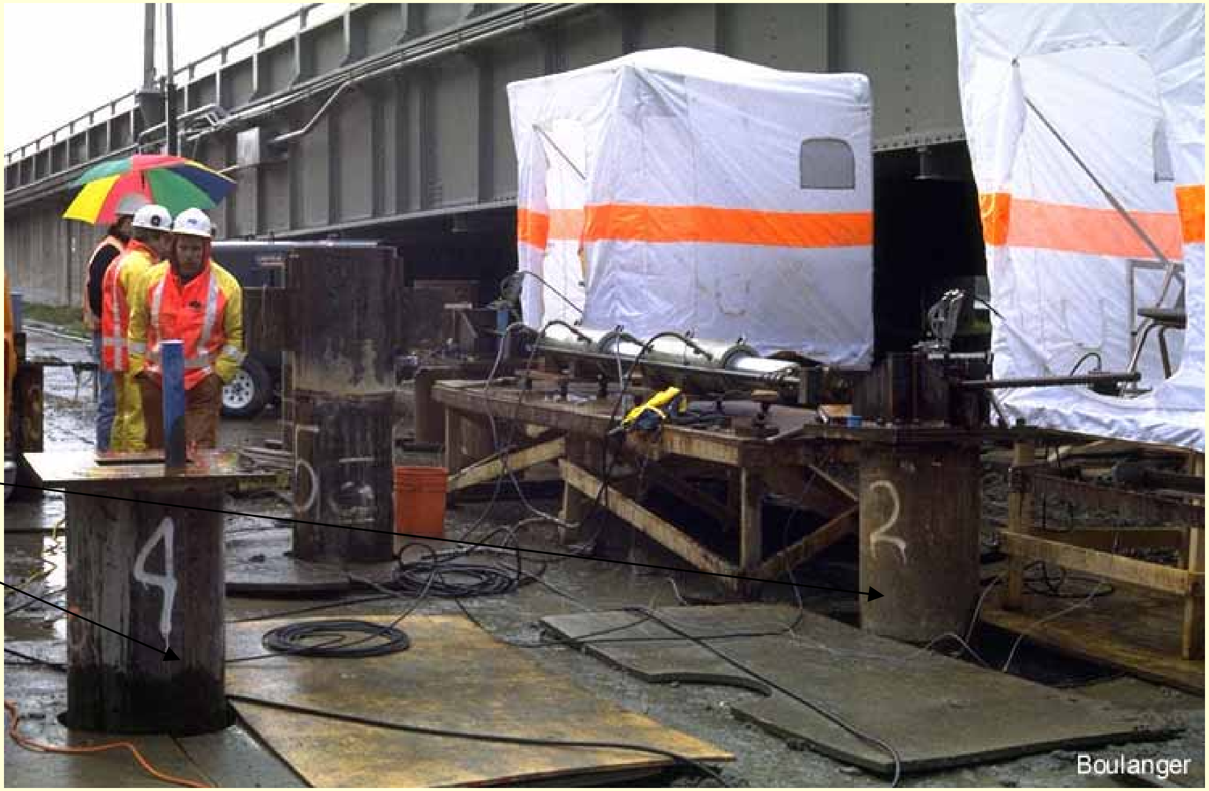
Lateral Load test

Just like axial capacity, lateral capacity of pile can also be obtained by conducting lateral load tests in the field



Steel Piles

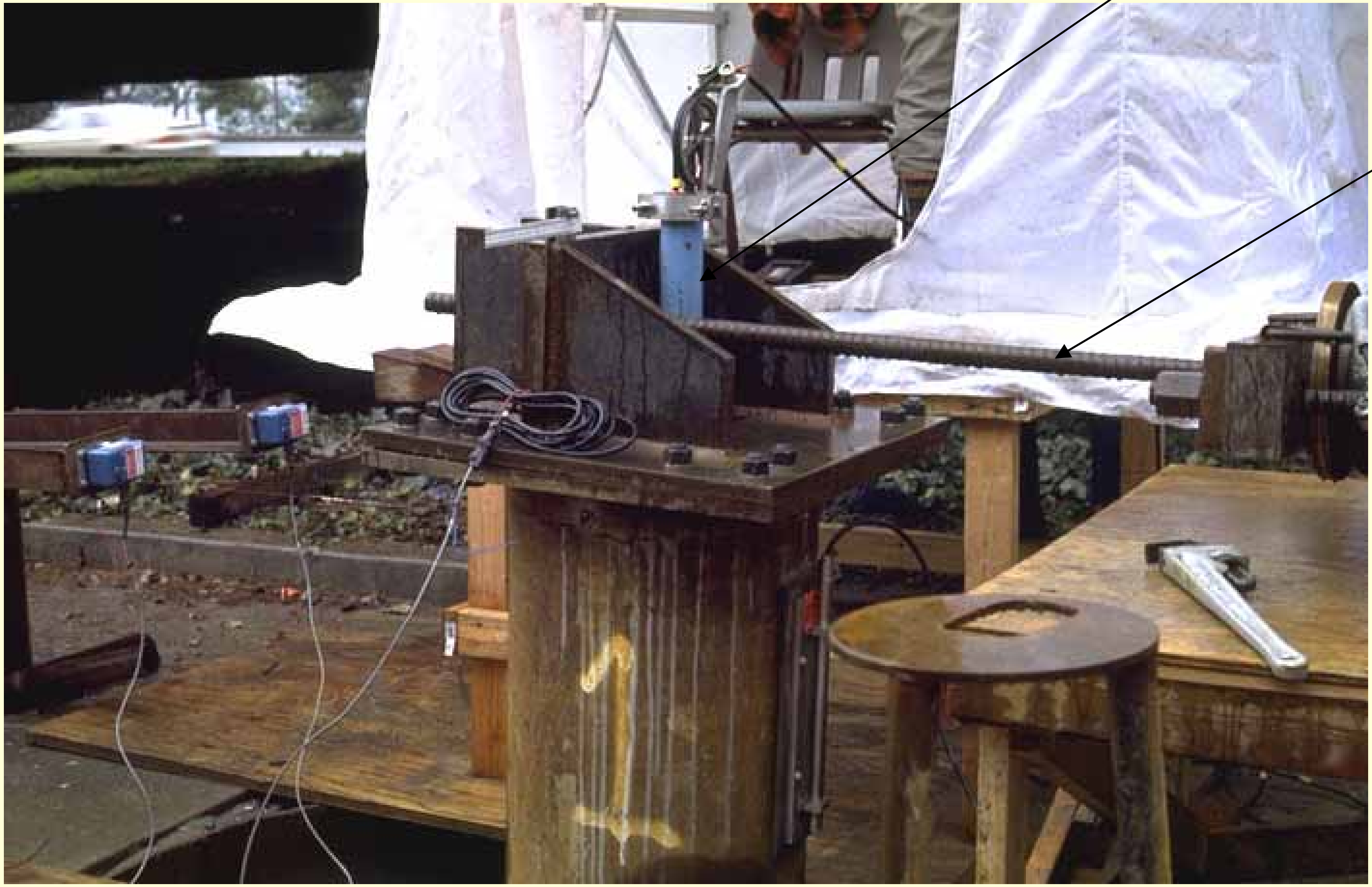
Typical lateral load test setup for steel piles – See pile No 2 in Picture.

Figure 11

Contd. next slide

inclinometer

Loading
rod



Lateral Loading is applied through the rod on to the pile by means of a Hydraulic jack

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Figure 12

Pullout or Tension Capacity – Field test

Just like axial pile load test, pullout load test is done by applying load in the opposite direction

The load test setup is similar to the axial compressive load test with little modifications.

Typical Pullout/Tensile load test setup

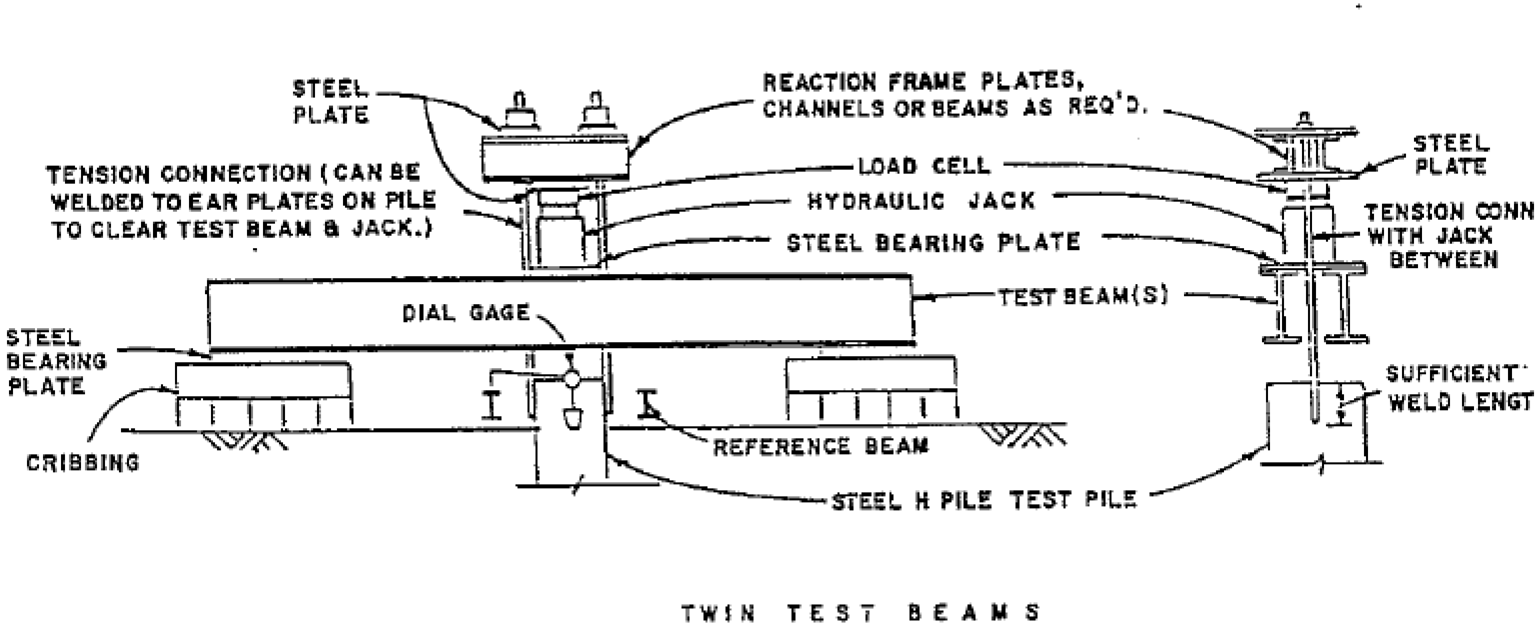


Figure 13

Theoretical Approach

Data required

- Soil parameters like cohesion c, angle of internal friction ø, adhesion factor between soil and pile material, etc.
- SPT Values (N values).
- Average cone resistance in case of CPT, etc.

Axial Capacity

The fundamental equation for axial capacity of pile is

$Q_U = Q_b + Q_s$

Where

Q_U = Ultimate Load carrying capacity of pile
Q_b =End bearing resistance= $q_b A_b$
Q_s = Skin friction resistance= $f_s\ A_s$

Where

q_b = Ultimate unit bearing capacity at base
A_b = Bearing area of the pile base
f_s = Unit skin friction
A_s = Surface area of the portion of pile embedded in soil.

$Q_b = q_b A_b$

Where

q_b = unit point bearing capacity (similar to bearing capacity of shallow foundation)

$= c' N_c^* + q' N_q^* + \gamma D N_\gamma^*$

c' = effective cohesion of the soil supporting pile tip

q' = effective vertical stress at the level of pile tip

D= width of the pile

γ= unit weight of the soil

N_c^* N_q^* N_γ^* are bearing capacity factors that include shape and depth factors

In the bearing capacity equation the term γ D N_γ^* can be neglected with very small error as D is relatively small compared to length of the pile.

- Researchers Meyerhoff, Vesic, etc have suggested various methods for the estimation of Q_b

- The methods proposed by various researchers primarily focused on determination of the parameters N_c^* N_q^* N_γ^*

(Refer the book “Principles of Foundation Engineering by B.M.Das -5th Edition” for the above methods)

$Q_s = f_s A_s$

Where

f_s = unit frictional resistance

A_s = Surface area of the pile

For determining f_s three methods are commonly used and they are called the **α-method, β-method and λ-method**

(Refer the book "Principles of Foundation Engineering by B.M.Das- 5th Edition" for the above methods)

Lateral Capacity of Piles

- Piles are subjected to lateral loads in addition to axial loads

- However for simplicity a pile subjected to only lateral load is usually studied for analytical convenience.

- Unlike axial capacity, the determination of lateral capacity of the pile is a complex problem.

- The lateral capacity of piles tested in the field is dictated by the lateral deflection criteria of local codes

A vertical pile resists lateral load by mobilizing passive pressure in the soil surrounding it.

The degree of distribution of the reaction of surrounding soil depends on the following

- The stiffness of the surrounding soil
- The stiffness of the pile
- The fixity of the ends of the pile

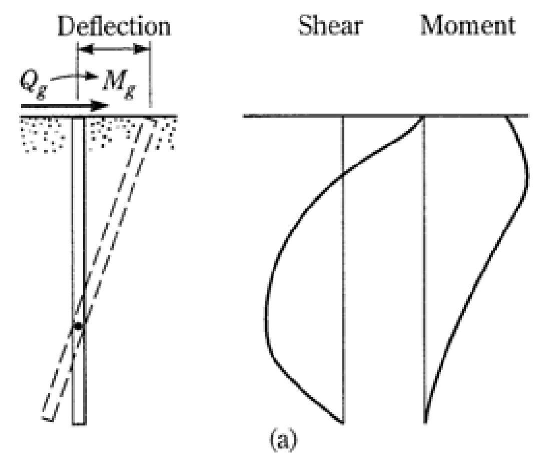
- The laterally loaded pile unlike an axially loaded pile is a three dimensional problem.

- In case of circular pile, the problem can be analyzed as two-dimensional due to symmetry.

- A laterally loaded pile can deflect in any direction depending on the direction of the lateral load.

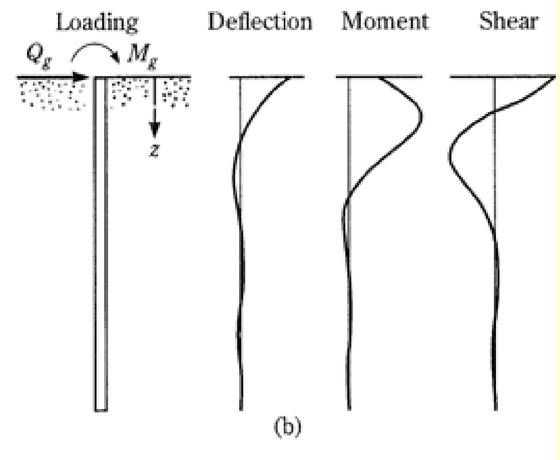
Categories of laterally loaded piles

Laterally loaded piles are divided into two categories based on variation of deflection, shear and moment, as shown below



Rigid pile

Figure 14



Flexible pile

Figure 15

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The lateral capacity of a pile is usually defined as the load corresponding to a specified deflection of pile head from its plumb. The amount of this deflection is usually suggested by the local codes based on the structure(s) for which the pile foundation is designed.

Laterally loaded pile: theory

The stresses/forces mobilized immediately after the lateral load is applied, are depicted below (For piles of other shapes also the same forces are mobilized)

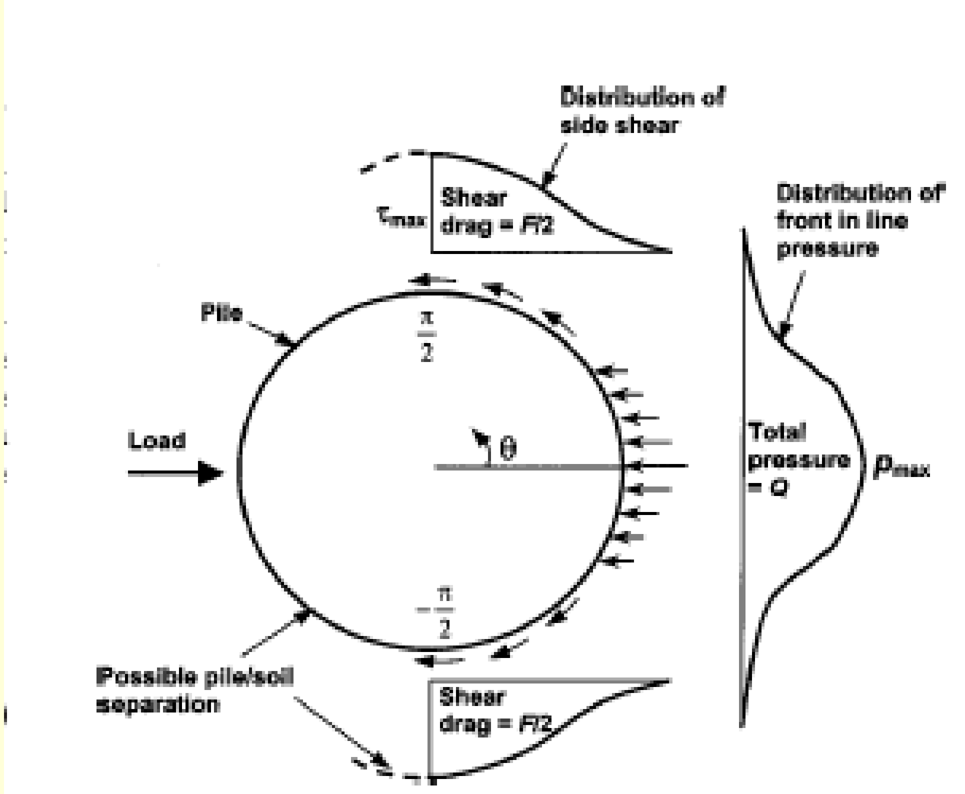


Figure 16: Forces mobilized around circular pile subjected to lateral loading(Plan view)

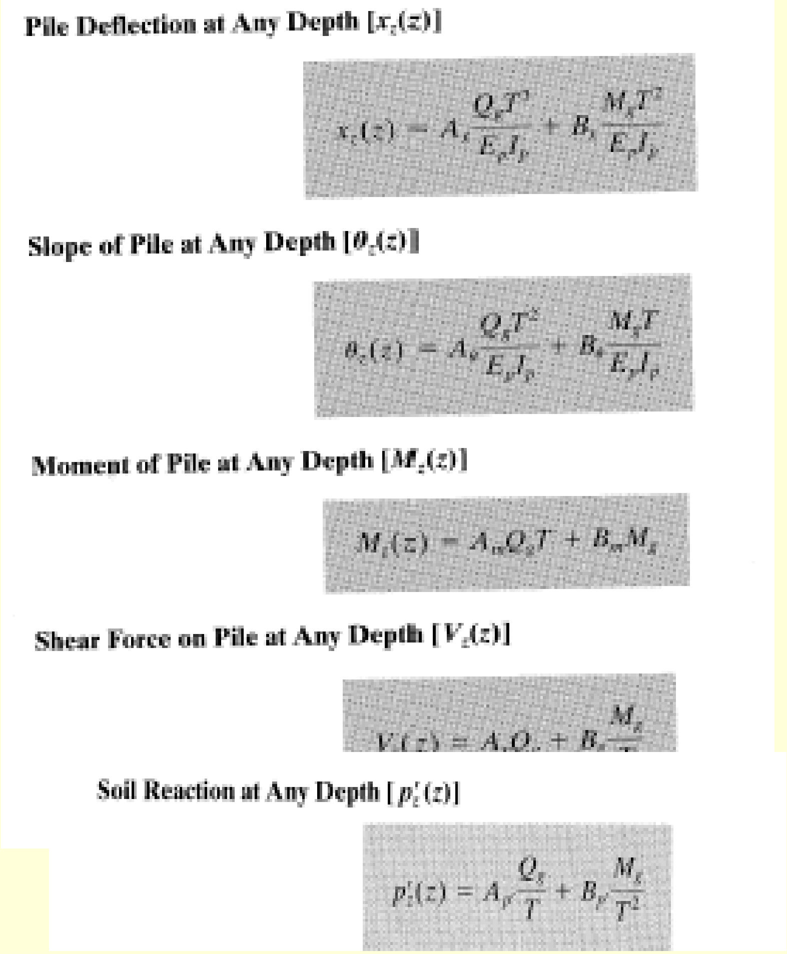
As shown in the Figure 7, the plane x-z is assumed to be the principal plane of the pile cross section. Due to the moment ‘Mo’ and shear ‘Vo’ applied at the pile head, each point on the pile undergoes a translation ‘u’ in the x-direction and rotation θ about y-axis.

The surrounding soil develops pressures ‘p’ at each point to resist the lateral displacement ‘u’ of the pile.

The principles of continuum mechanics and correlations with the results of tests on instrumented laterally loaded piles were used to relate ‘u’ at each point with corresponding ‘p’. The relationship between ‘p’ and ‘u’ is presented as non-linear curve famously known as p-u curve (in some literature referred as p-y curve).

All p-u curves are developed for monotonically increasing static loads and the static curve is then altered by various techniques to account for degradation effects due to cyclic loading

A general method for moments, shear forces and displacements for a vertical pile embedded in a granular soil and subjected to moment and shear at the ground surface as shown in Figure 7 was given by Matlock and Resse(1960). The following are the equations proposed by them based on theory of beam on elastic foundation



Pile Deflection at Any Depth [$x_z(z)$]

$$x_z(z) = A_x \frac{Q_g T^3}{E_p I_p} + B_x \frac{M_g T^2}{E_p I_p}$$

Slope of Pile at Any Depth [$\theta_z(z)$]

$$\theta_z(z) = A_\theta \frac{Q_g T^2}{E_p I_p} + B_\theta \frac{M_g T}{E_p I_p}$$

Moment of Pile at Any Depth [$M_z(z)$]

$$M_z(z) = A_m Q_g T + B_m M_g$$

Shear Force on Pile at Any Depth [$V_z(z)$]

$$V_z(z) = A_v Q_g + B_v \frac{M_g}{T}$$

Soil Reaction at Any Depth [$p_z'(z)$]

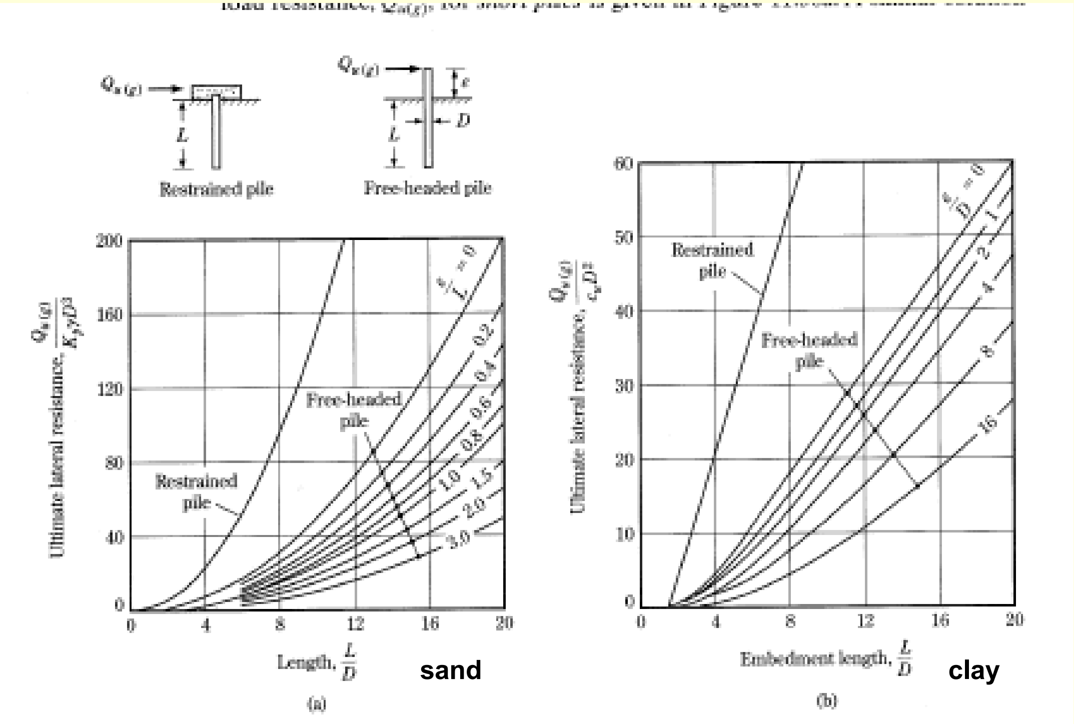
$$p_z'(z) = A_{p'} \frac{Q_g}{T} + B_{p'} \frac{M_g}{T^2}$$

Simplified solution

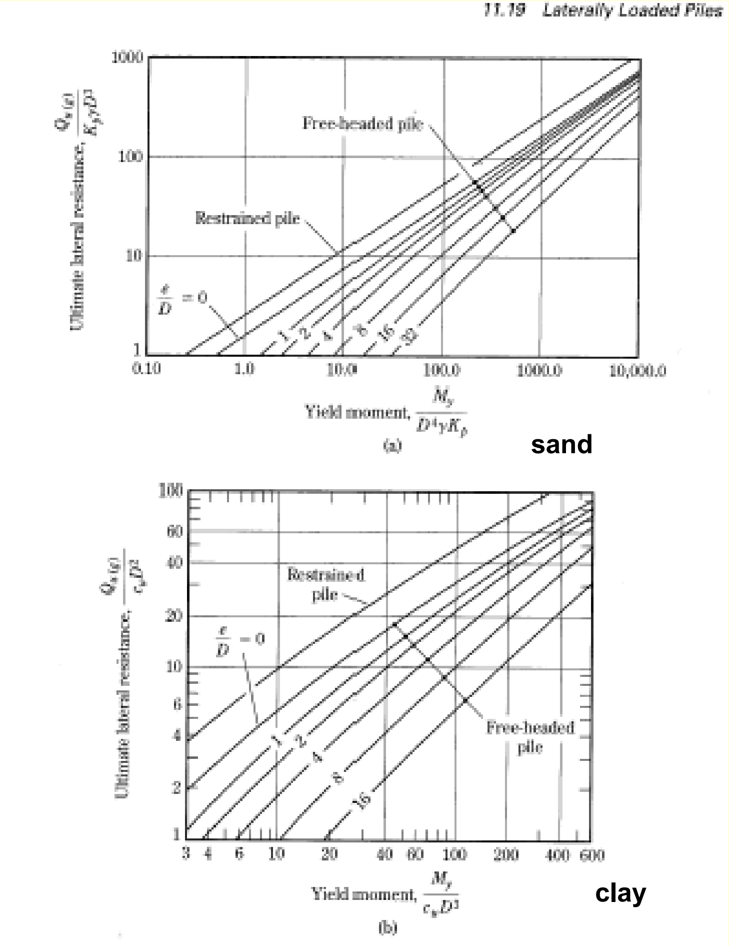
Broms (1965) developed a simplified solution for ultimate lateral resistance of piles based on the following assumptions.

- shear failure of surrounding soil (in case of rigid piles)
- bending of the pile by plastic yield resistance of pile section (in case of flexible piles)

Broms’s solutions for ultimate resistance of rigid and flexible piles are shown in the next slide



(a)



(b)

Broms's solution for ultimate resistance of rigid piles (a) and flexible piles (b)

Figure 17

Uplift Capacity of Piles

The major components resisting uplift forces on pile foundation are skin friction and self weight of the pile.

(refer Figure 8)

So the governing equation for uplift capacity is

↑

Frictional resistance

$Q_{uplift} = f_s\ A_s$ + Weight of the pile

The capacity of the pile (Axial/Lateral/Uplift) either arrived by field approach or theoretical approach is called Ultimate capacity which is divided with a factor to arrive at safe carrying capacity of the pile.

The ultimate capacity is usually dictated by the limitations on settlements as per local engineering codes

The main purpose of under reporting the pile capacity by dividing it with a factor of safety is to accommodate various un certainties in

- Soil strata
- Loading and
- Possible reduction in strength of sub soil strata due to installation technique, etc.

Pile groups

- Most pile foundations contain group of piles instead of single pile
- The supporting capacity of a group of ‘n’ similar piles in many cases (not in all cases) is ≤ ‘n’ times the capacity of a single pile- reason being the zone of soil or rock stressed by the entire group extends to much greater width and depth than that by a single pile as shown in the figure

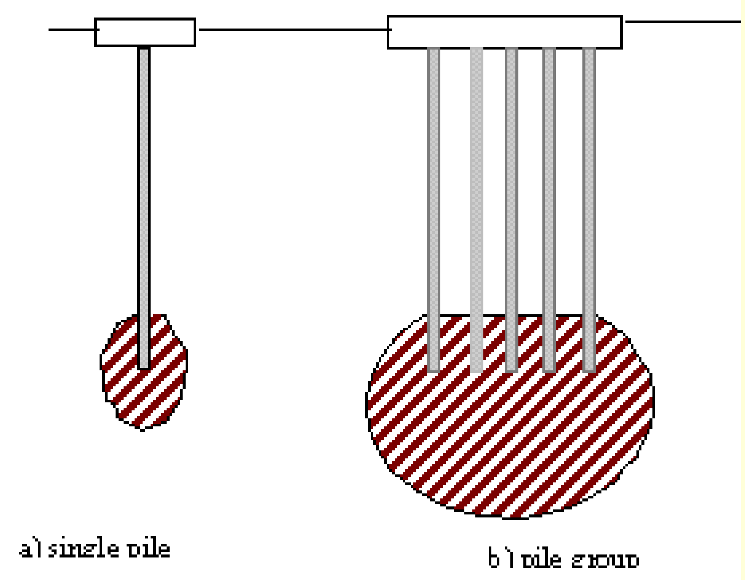


Figure 18

Analysis of pile groups

There are three methods commonly used to analyze pile group:

- Simple static analysis: This method ignores the presence of soil and assumes pile group as an isolated structural system. It also assumes zero moment at the head of each pile.

- Equivalent bent analysis: This method considers the soil sub grade reaction on the equivalent free standing length of the piles. The pile cap is assumed to be rigid and piles are assumed to behave elastically.

- Elastic continuum analysis: The soil is considered as elastic material that is consistent through out its mass.

In comparing various methods of analysis, the vertical loads are similar, but elastic continuum method predicts higher maximum load.

The equivalent bent method which ignores presence of soil predicts higher pile rotations/moments than elastic continuum method.

Pile group efficiency factor(η) is usually calculated using any of the following six methods

1) Converse labarre's method

$$\eta = 1 - \left[\frac{(n_1 - 1)n_2 + (n_2 - 1)n_1}{90\, n_1 n_2} \right] \theta \qquad where\ \theta(\text{deg}) = \tan^{-1} \frac{d}{s}$$

Where, 'n_i' represents no. of rows and columns 'd' is the dia of the pile and 's' c/c spacing between adjacent piles.

2) Feld’s rule: reduces the capacity of each pile by 0.0625 for each adjacent pile. The spacing of piles is not considered.

3) Contractor’s rule: The pile capacity is reduced by a factor **I** for each adjacent pile where **I =d/8s**

4) Sand’s rule: Used for pile carried through friction in sand

$$\eta = \frac{2[(n_1 + n_2 - 2) + 4d]}{p\, n_1 n_2}$$

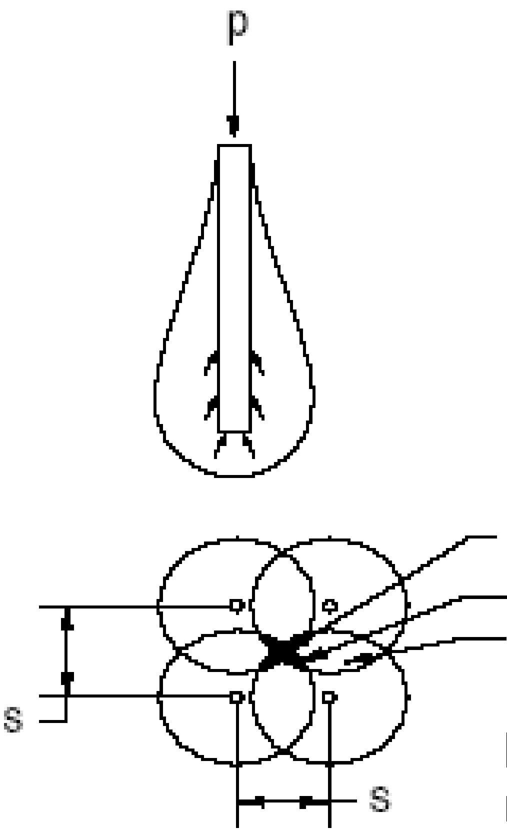
5) Los Angles group action method:

$$\eta = 1 - \frac{D}{\pi d\, n_1 n_2}\left[n_1\left(n_1 - 1\right)\right)\right] + n_1\left(n_1 - 1\right) + \sqrt{2}\left(n_1 - 1\right)\left(n_2 - 1\right)$$

6) Seiler- Keeney method:

$$\eta = \left\{1 - \left[\frac{11\,d}{7\left(d^2 - 1\right)}\right]\left[\frac{(n_1 + n_2 - 2)}{n_1 + n_2 - 1}\right]\right\} + \frac{0.3}{n_1 + n_2} \quad \text{where } d \text{ is in feet}$$

Stresses coming from the piles in the soil mass overlap when the piles are placed too close to each other. The load-bearing capacity of each pile should therefore be reduced. The following is a simplified analysis to obtain the group's efficiency for friction piles in sand.



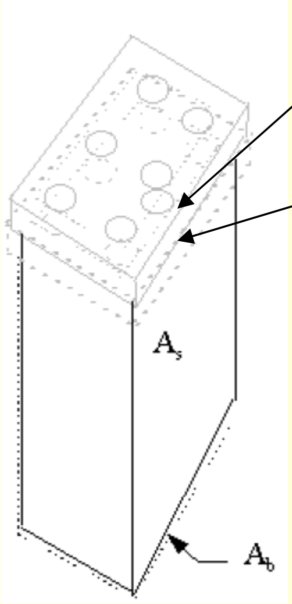
4 piles contribute to the stress in this zone
3 piles contribute to the stress in this zone
2 piles contribute to the stress in this zone

Note that adequate spacing of the piles reduces the overlap zones and number of piles contribute to any zone

Stress surrounding a friction pile and the summing effects of a pile group

Important points to remember regarding pile groups

- Pile groups driven into granular soils may provide reinforcement to soil and the group efficiency factor may reach up to 2.
- In contrast the efficiency factor of pile group driven into cohesive soils may be less than 1.
- Under axial or lateral load, instead of failure of individual piles in the group, block failure may arise as shown in the below figure



Initial position of the block

Position of block after settlement

Figure 19

- independent calculations showing the capacity of block or group of pile and capacity of individual piles should be made

- Relate the ultimate capacity of the block to sum of ultimate capacities of individual piles in the group i.e. find the ratio of ultimate capacity of block to sum of ultimate capacities of all piles in the group. This ratio should not be preferably less than 1

Ultimate Axial Capacity

Ultimate capacity of pile group is usually the smaller of

a) Ultimate capacity = m x n (ultimate capacity of single pile in the group)

where m= no. of rows and n= no. of columns in the group (in plan view)

b) Ultimate capacity = L * B *(unit bearing resistance) + 2*(L+B) *Unit frictional resistance

Where L& B are plan dimensions of imaginary block encircling the pile group

Note the above formulae are based on the assumption that the line of action of loading coincides with the C.G of the group (i.e no moments)

Ultimate Uplift Capacity

The pile group's efficiency against uplift η_T is given by, where T is the uplifting force.

$$\eta_T = \frac{T_g}{T_i}$$

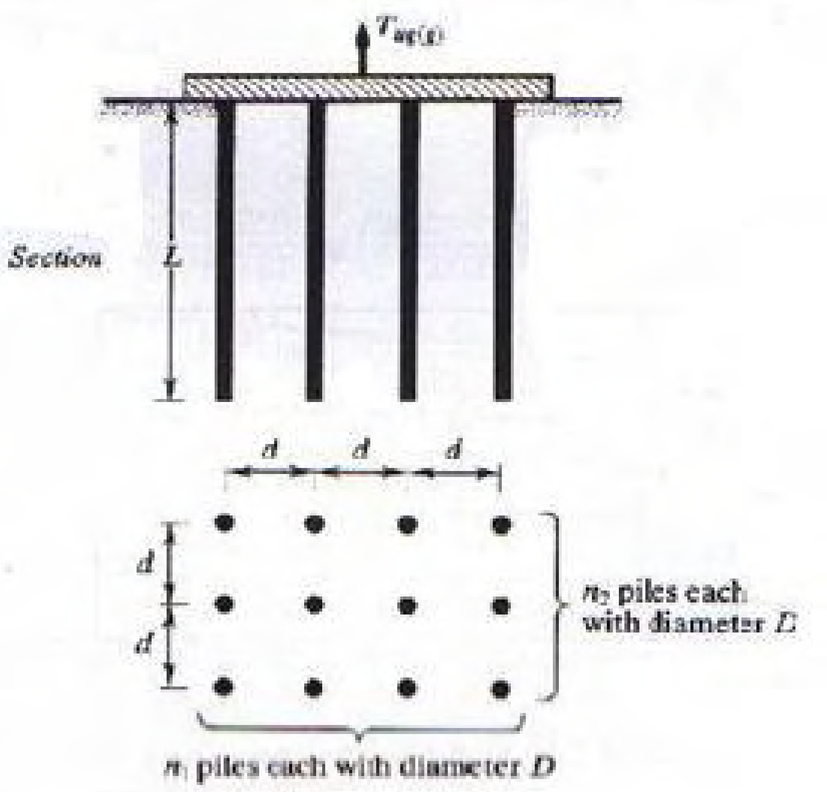

$T_{ug(g)}$
Section
L
d
d
d
d
d
n_2 piles each with diameter D
n_1 piles each with diameter D

Figure 20

where **T$_g$** is the combined uplift capacity of group and **T$_i$** sum of uplift capacities of all individual piles

Ultimate Lateral capacity

There are two common problems in the analysis of pile groups subjected to lateral loading

1. The computation of loads coming on to each pile in the group and
2. The computation of efficiency of group of closely spaced piles.

The ultimate lateral capacity, unlike axial capacity, of pile group cannot be presented as a simple equation due to the mathematical difficulty in establishing a proper relationship between the following INTERACTING FACTORS in addition to those associated with determining the lateral capacity of single pile.

- Stiffness and density of soil in front of the pile cap
- Depth of cap embedment in the soil
- Rotational restraint at the pile head by virtue of its embedment into the pile cap
- Pile group axial capacity
- Stiffness and density of soil around the piles
- Location of Pile cap i.e. above or below soil
- Cyclic and sustained loads

However, an analytical method called Group Equivalent Pile (GEP) method can be used with considerable accuracy for developing p-u curves for pile cap and piles in the group. In GEP, p-u curves are obtained by multiplying the ‘p’ values of single pile with a modification factor to account for interaction effects and summing the modified ‘p’ values of all piles in the group to obtain p-u curves for the group

Factors influencing pile capacities

- The surrounding soil
- installation technique like driven or bored
- Method of construction (pre cast or cast in situ)
- Spacing of piles in a group
- Symmetry of the group
- Location of pile cap i.e. above or below soil
- Shape of the pile cap, etc.
- Location of pile in the group
- Drainage conditions in soil

Go through references given at the end of presentation to learn about theoretical determination of pile capacities due to the reasons mentioned above

Settlement Analysis

Piles are subjected to the settlement due to the vertical loads coming on to them from the structure supported by them.

The total settlement of a single pile has the following components

- Elastic settlement of the pile (se1)
- Settlement of the pile caused by the load at the pile tip(se2)
- Settlement of the pile caused by load transfer along the pile shaft (se3).

The formulae for calculating the above –mentioned settlements are given in the next slide

$$se1 = \frac{(Q_{wp} + \xi Q_{ws})L}{A_p E_p}$$

$$se2 = \frac{q_{wp} D(1 - \mu^2) I_{wp}}{E_s}$$

$$se3 = \frac{Q_{ws} D(1 - \mu^2{}_s) I_{ws}}{\rho L E_S}$$

Where,

Q_{wp} = load carried at the pile tip resting on the soil, under working load condition

Q_{ws} = load carried by skin friction under working load condition

L= Length of the pile

E_p = Modulus of elasticity of pile material

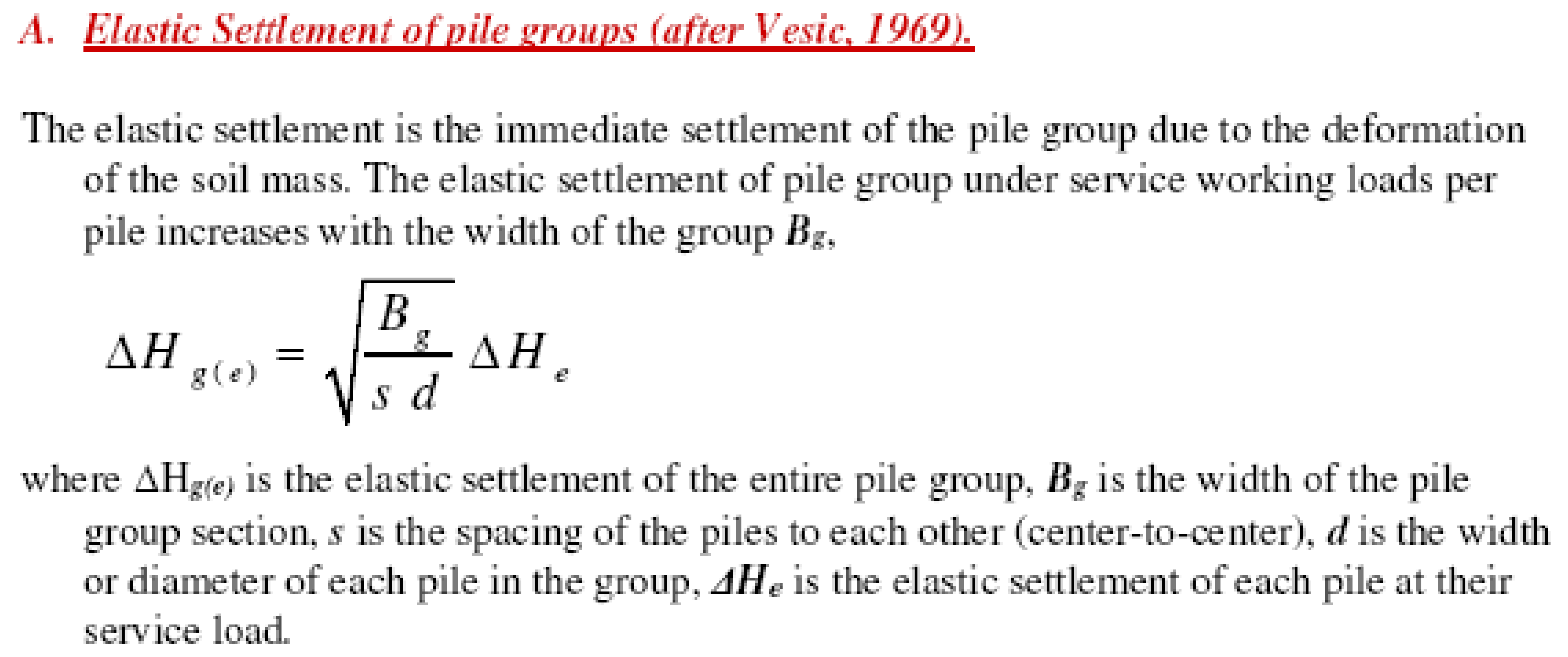
A_p = Area of cross section of pile material

q_{wp} = load at pile tip per unit area

μ_s = poissons ratio of the soil

I_{wp} I_{ws} = influence factors

Settlement of pile groups



A. *Elastic Settlement of pile groups (after Vesic, 1969).*

The elastic settlement is the immediate settlement of the pile group due to the deformation of the soil mass. The elastic settlement of pile group under service working loads per pile increases with the width of the group B_g,

$$\Delta H_{g(e)} = \sqrt{\frac{B_g}{s\ d}}\,\Delta H_e$$

where $\Delta H_{g(e)}$ is the elastic settlement of the entire pile group, B_g is the width of the pile group section, s is the spacing of the piles to each other (center-to-center), d is the width or diameter of each pile in the group, ΔH_e is the elastic settlement of each pile at their service load.

C. Consolidation settlement of Pile Groups.

The simple stress distribution below the pile group is the 2:1 stress method,

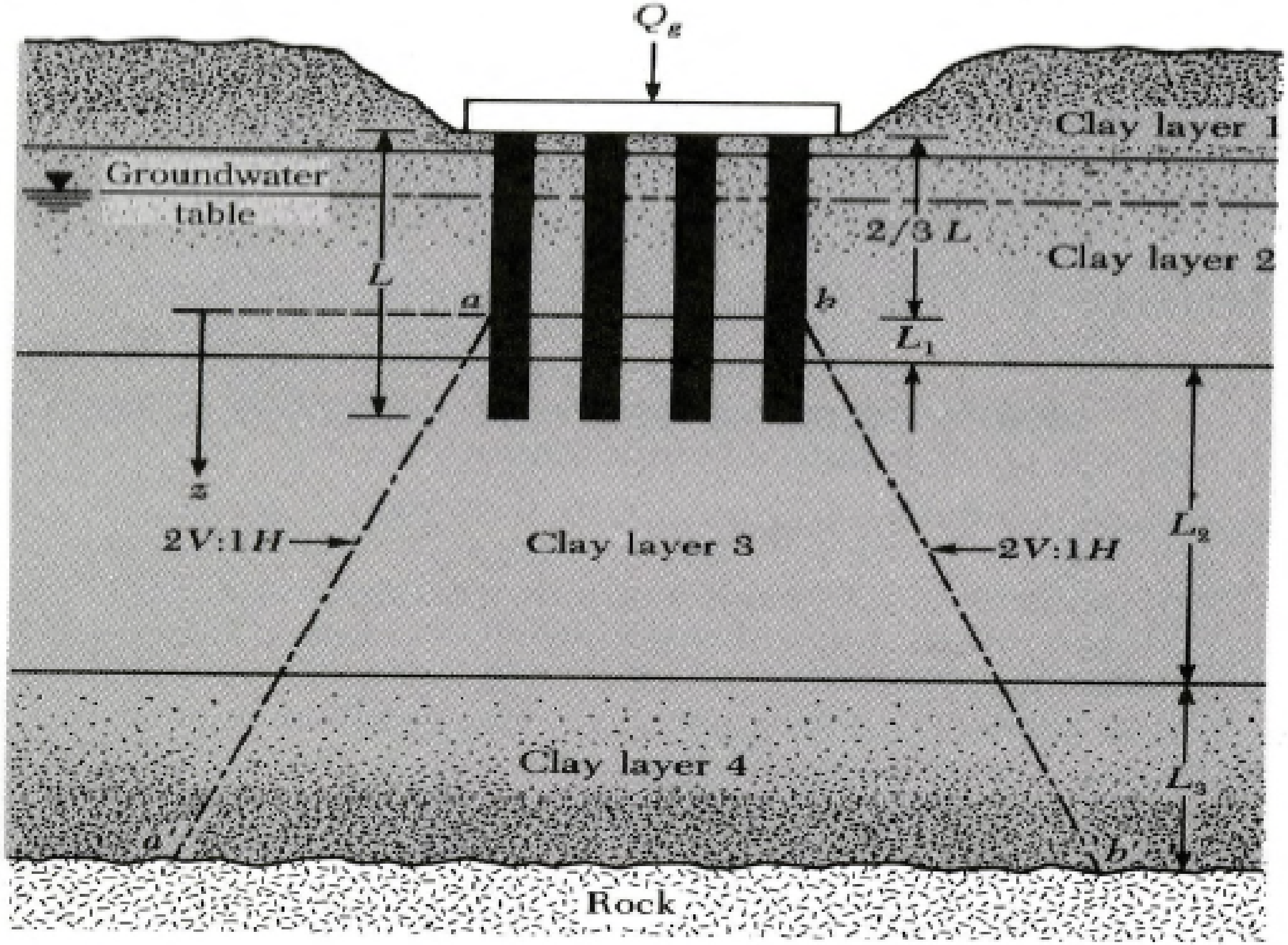
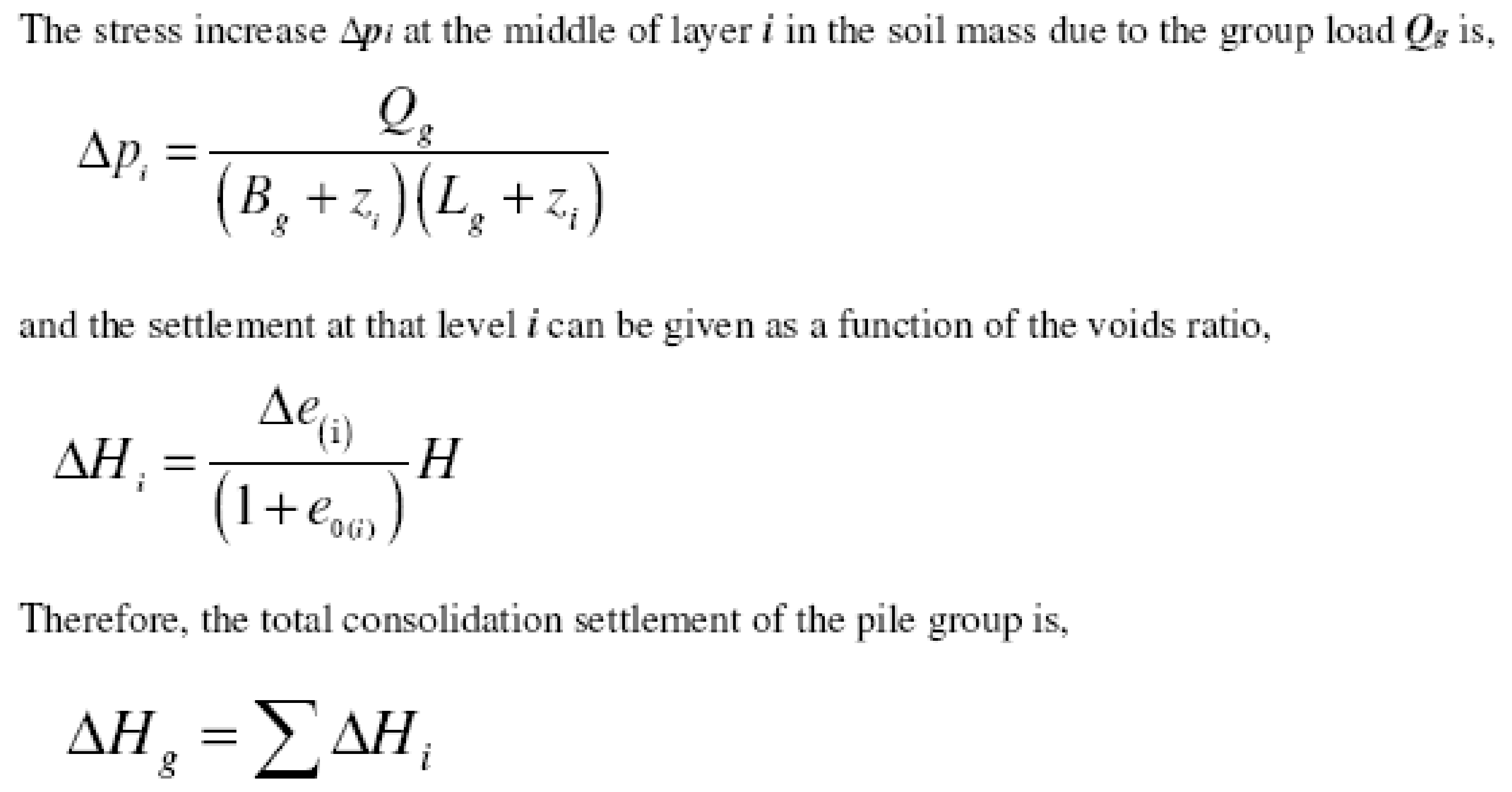


Figure 21



The stress increase Δp_i at the middle of layer i in the soil mass due to the group load Q_g is,

$$\Delta p_i = \frac{Q_g}{\left(B_g + z_i\right)\left(L_g + z_i\right)}$$

and the settlement at that level i can be given as a function of the voids ratio,

$$\Delta H_i = \frac{\Delta e_{(i)}}{\left(1 + e_{0(i)}\right)} H$$

Therefore, the total consolidation settlement of the pile group is,

$$\Delta H_g = \sum \Delta H_i$$

Design Steps

Design of pile foundation involves the following steps

1)Calculating the ultimate and then safe carrying capacity of pile of given material for a given soil data using the theoretical methods or obtaining the above-mentioned capacity from field test.

2)Arriving at the number of piles required for a given loading from the structure by considering the group effects on piles.

3)Designing the pile cap, which is usually considered as rigid member in a pile group.

4) Calculating the distribution of forces , from the superstructure, in the piles and ensuring that the force on any pile in a group doesn’t exceed its safe carrying capacity.

5) Finally carrying out settlement analysis to ensure that the settlements are within the limits

Note: There are several mathematical procedures for calculating the capacity in various kinds of soil viz. cohesive, granular, and cohesive-granular and also to calculate the capacity based on method of installation i.e. driven or bored. Please refer the literature given in the references at the end to understand the procedures.

2.SPECIAL TOPICS

Negative Skin Friction

What is negative skin friction?

Negative skin friction is a downward shear drag acting on the pile surface due to relative downward movement of soil strata surrounding the pile.

The following are some of the causes of negative skin friction

- Due to pile or pile segment passing through compressible soil stratum which consolidates

- Due to placement of a fill on compressible soil layer causing the layer to consolidate

- Lowering of ground water table causing the shrinkage of expansive soils.

- Under consolidated natural or compacted soils.

If the pile tip is on a stiff or hard stratum, there will be a relative downward movement of upper compressible layer of soil w.r.t. pile , due to above causes, causing a downward drag force.

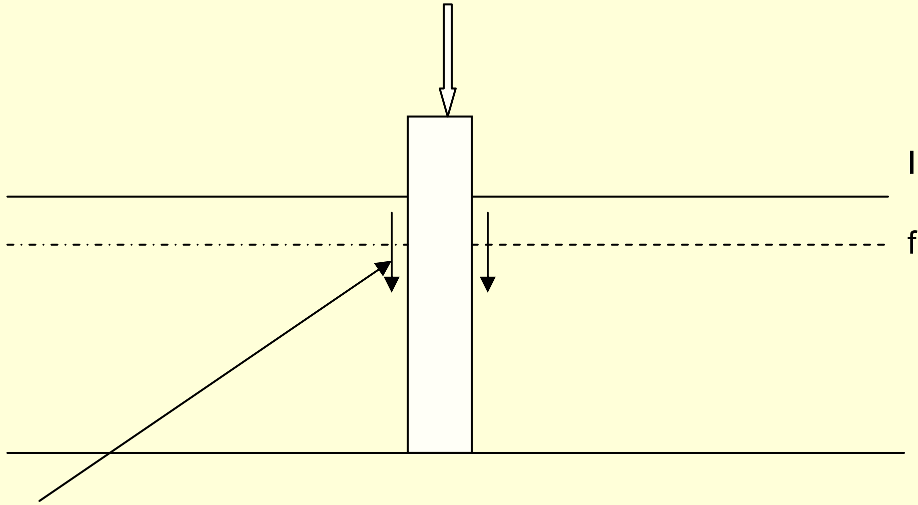

Initial position of compressible deposit
final position of compressible deposit
Downward drag(negative skin friction)

Figure 22

- Vesic stated that downward movement as little as 0.6 inch may be sufficient to mobilize full negative skin friction.

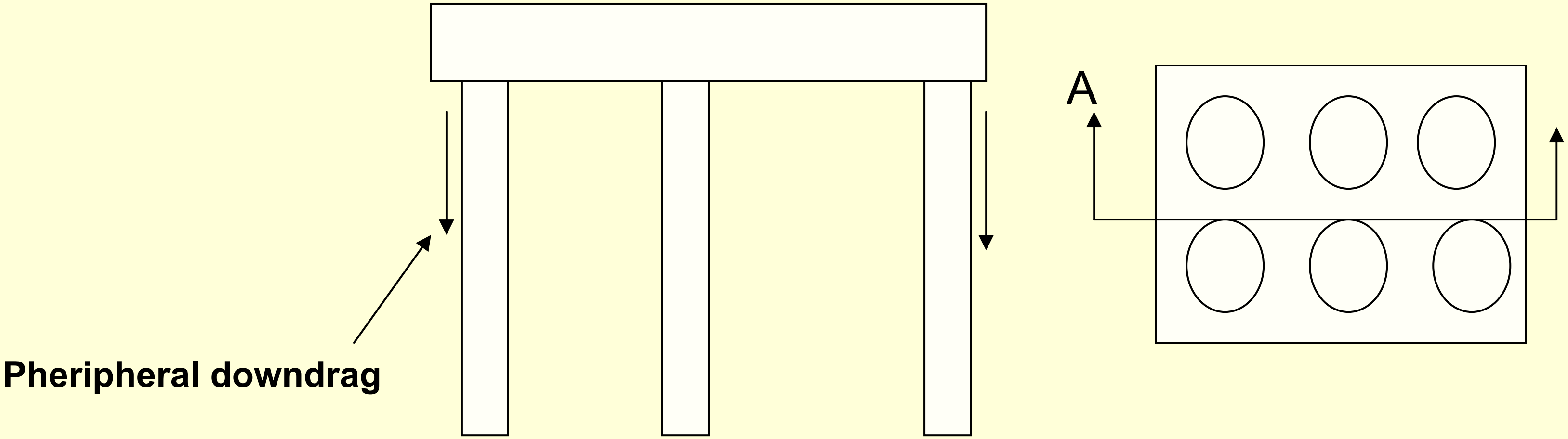
- The down drag will not affect the geotechnical capacity of end-bearing piles but will increase stresses on the pile and pile cap.

The negative skin friction of a single pile is given by

Negative skin friction load = Unit frictional resistance (downward)* Length of the pile above bottom of the compressible layer * Perimeter of the pile cross section

And total downward load= negative skin friction load + live load + dead load

For a pile group it can be assumed that there is no relative movement between the piles and the soil between the piles. Therefore the total force acting down is equal to the weight of the block of soil held between the piles, the weight of the piles and the pile cap and the downward drag along the pile group perimeter due to negative skin friction



SEC A

Figure 23

Socketed Piles

What are socketed piles?

Socketed piles are usually end bearing piles which are socketed into a weathered/soft rock.

What is weathered rock?

- **Soil consolidates to Rock**
- **Rock weathers to Soil**

The in between phase of the above two is called as weathered rock /soft rock

Pile Socketed into weathered rock

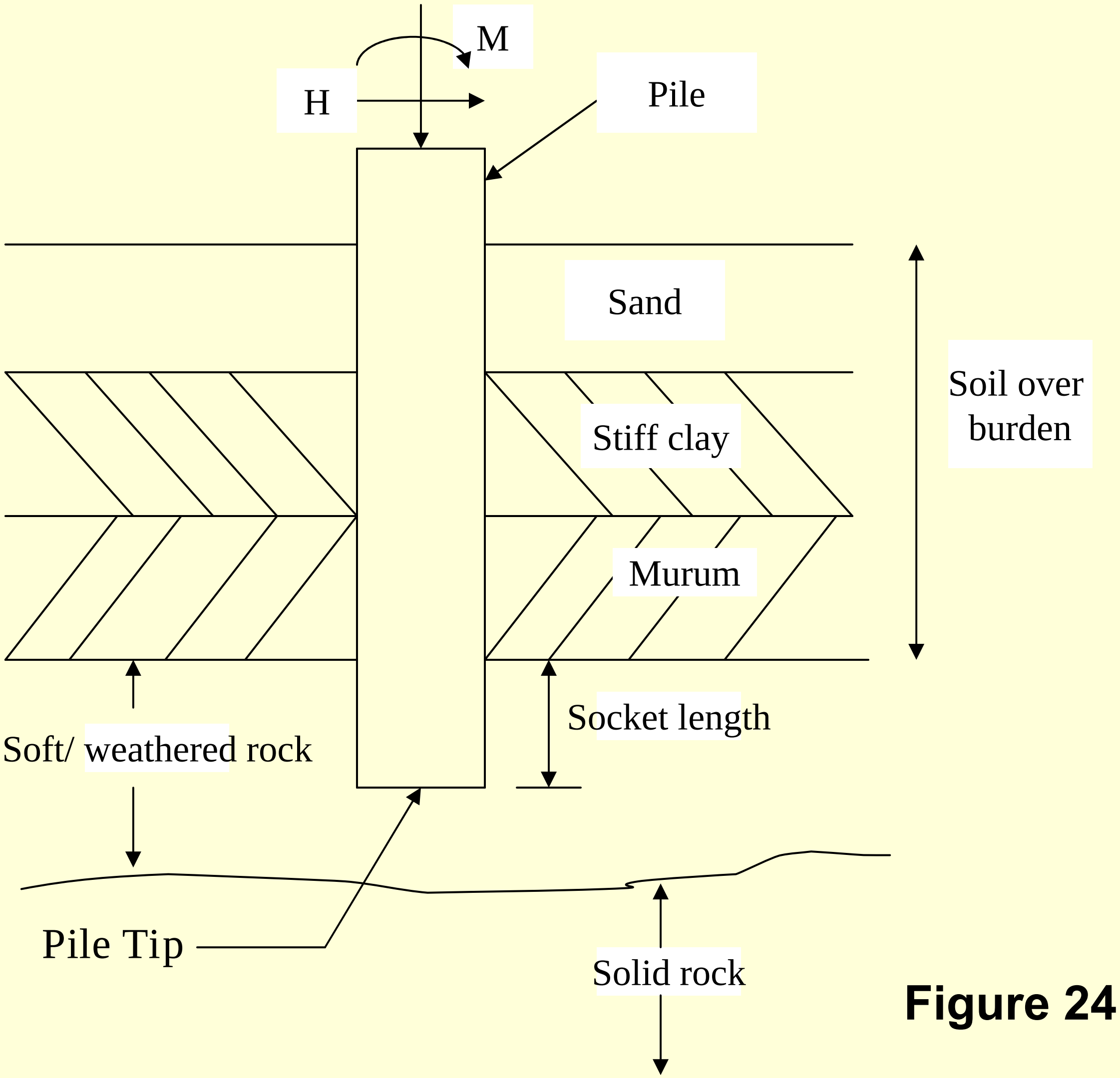


Figure 24

Why socketing?

The common belief is socketing pile into a soft or weathered rock will improve the capacities of piles to lateral loads when the surrounding soil above the rock is weak.

The depth of socket is designed based on

- Local experience/empirical formulae: Usually a socket of depth varying from 2 to 5 times the diameter of the pile.

- By a more systematic approach called COLE and STROUD approach (is not discussed here as it out of scope of this presentation)

Dynamic testing of Piles

Dynamic pile testing is fast and effective method for assessing bearing capacity of the foundation that requires instrumenting deep foundations with accelerometers and strain transducers and analyzing the data collected by these transducers.

The Procedure is standardized by ASTM D 4945 (Standard test method for high strain dynamic testing of piles.

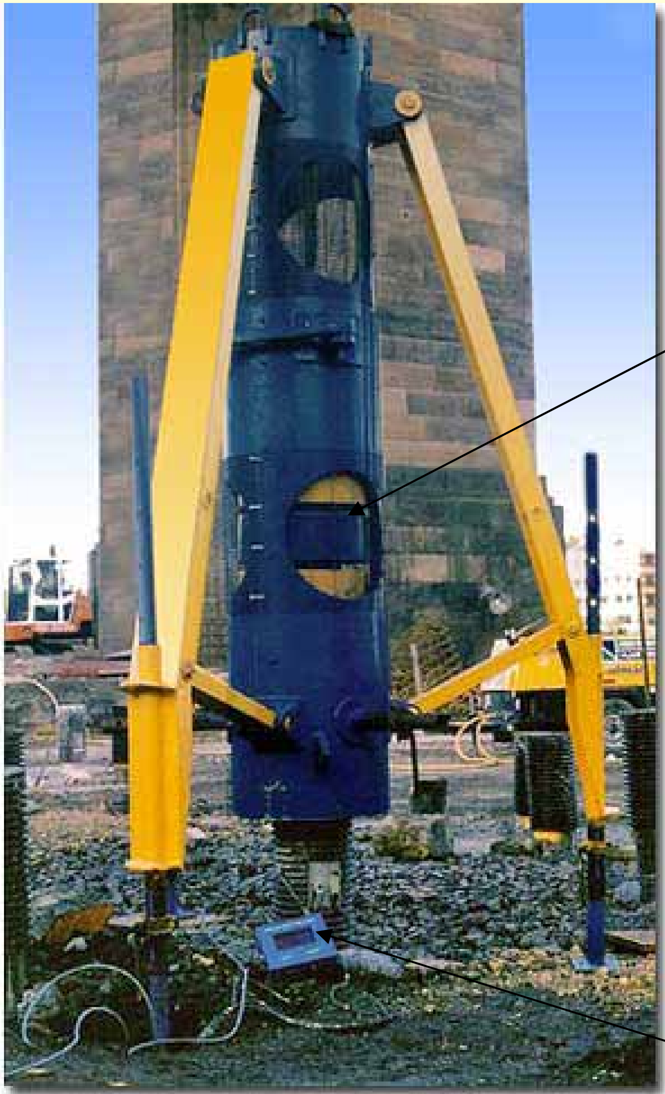
The testing in addition to bearing capacity gives shaft resistance and point bearing resistance distribution and also evaluates the shape and integrity (please refer pile integrity in this presentation for more details) of the foundation

- Dynamic pile testing is a supplement to static testing for evaluating pile capacity.

- The Dynamic pile testing is categorized as
  - ---- High strain dynamic testing and
  - ------Low strain dynamic testing

- High strain dynamic testing is used to provide data on force and acceleration of pile subjected to impact force. The data is used to evaluate the bearing capacity/capacity and structural integrity of the pile as well as hammer performance, pile stresses and soil characteristics like soil damping coefficients. Pile integrity which is accurately evaluated on site will allow the engineer to immediately reject or accept the pile.

- Low strain pile testing is exclusively used for testing integrity (continuity of pile). It also gives information on physical dimension and consistency of the pile material.



Dynamic pile load testing and stress analysis

Setup to produce impact on the pile

Data collector and Analyzer called pile driving analyzer (PDA)

Figure 25:Dynamic pile testing setup

Another picture showing setup for dynamic pile testing

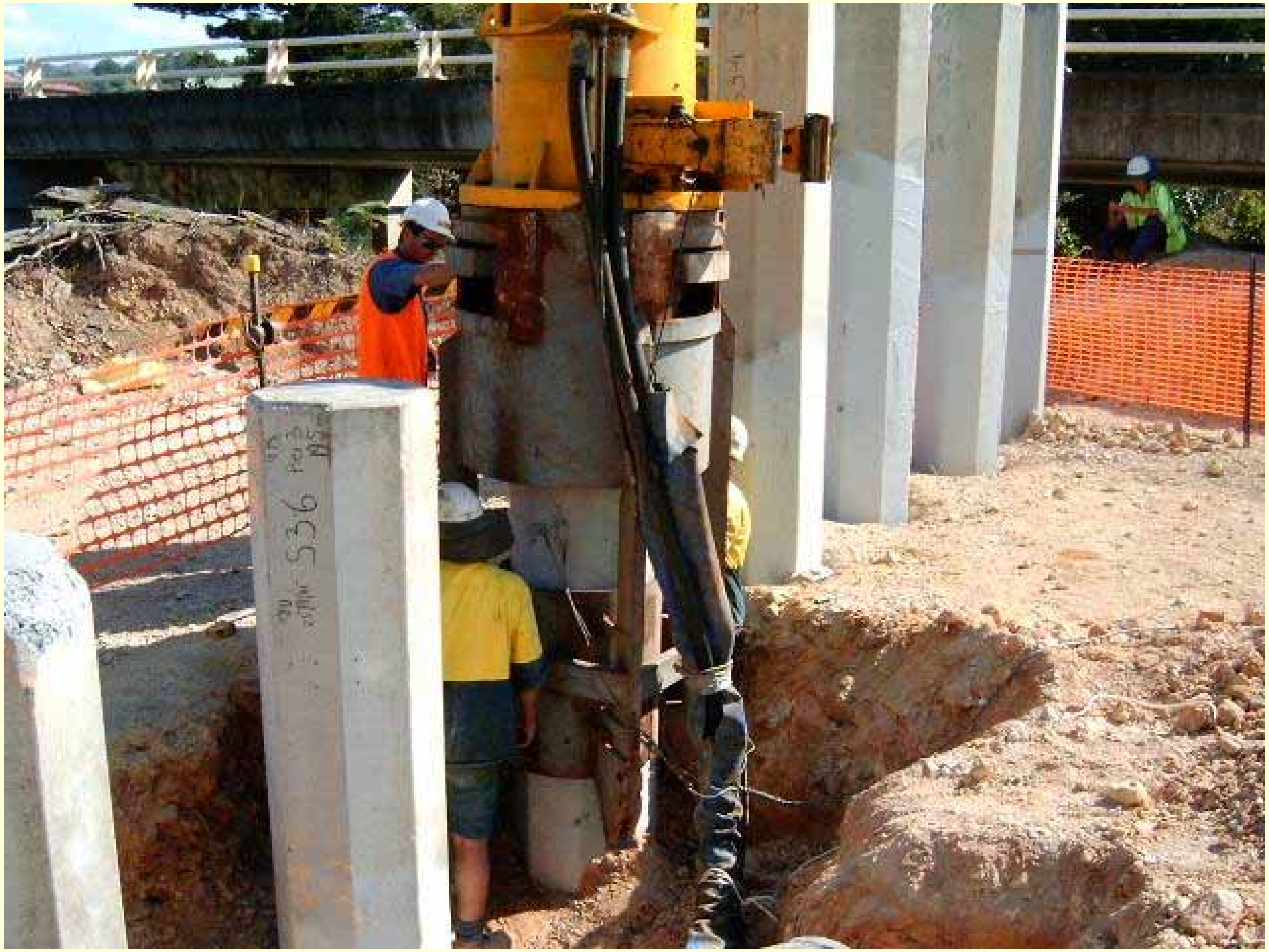


Figure 26

04/03/2009

The data obtained from dynamic pile testing i.e. force and velocity measurements of pile are fed to a software program called “ Case Pile Wave Analysis Program(CAPWAP) “ which is used to simulate static pile load test .

A typical CAPWAP procedure uses the following steps.

1.Retrieve data from pile driving analyzer (collects force and velocity data)

2.Setup pile model

3.Assume soil resistance parameters

4.Perform analysis using one of the measured quantities (force or velocity) as input and calculate the other.

5.Compare measured with computed quantity

6.If match is not satisfactory, adjust soil resistance parameters and go to step 4

7.Out put soil model when satisfactory match is obtained and simulate static test.

Pile integrity testing

What is pile integrity testing?

A pile integrity test also known as low strain dynamic testing is used to check

- Potentially dangerous defects such non uniform cross section, voids, cracks, etc in the casted pile foundation.
- Integrity of pile in its total length.
- To determine unknown length of pile in existing structures

When cast in-situ piles are constructed, the following defects may occur, hence the main objectives in the pile integrity testing is to provide the client/consultants information about :

a) honeycombing due to inadequate vibration.

b) segregation due to over vibration and improper concrete placement methods.

c) washouts of cement due to groundwater flow.

d) cracks in pile shaft due to shrinkage.

e) inclusion of foreign material causing contamination of the concrete.

f) necking of the pile due to collapse of side walls during withdrawal of the temporary casings

Dynamic loading on piles

The following are the most common situations in which piles are subjected to dynamic loading

- Pile driving
- Piles supporting dynamic equipment
- Earthquake

Pile driving

- Usually ‘Driven’ piles are driven into the ground by impact force which causes considerable stresses in the piles.

- The forces and accelerations induced in the pile during driving are recorded using a data logger called Pile Driving Analyzer(PDA).

- The data obtained by PDA will be used to study the pile integrity and potentially dangerous defects like honey combing, cracks, presence of foreign matter, etc.

- The PDA works on the principles of wave propagation.

Piles supporting dynamic equipment.

Piles supporting dynamic equipment are usually subjected to impact and periodic forces which act continuously for a long time. This results in a complex soil- structure problem which calls for a rigorous analysis. Foundation for dynamic equipment is its self a research area. To give a preliminary idea some figures are presented below.

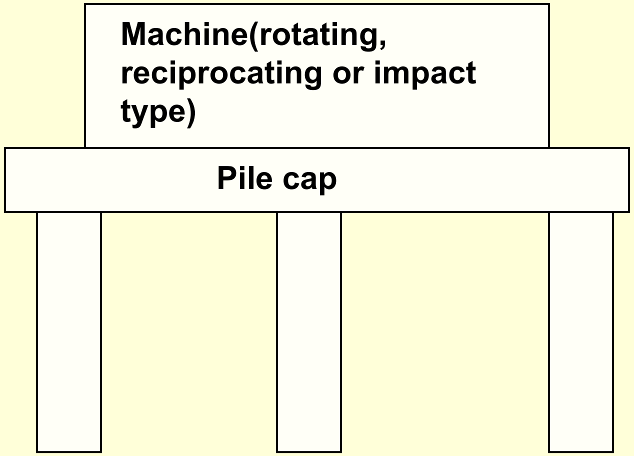


Figure 27:Machine on pile foundation

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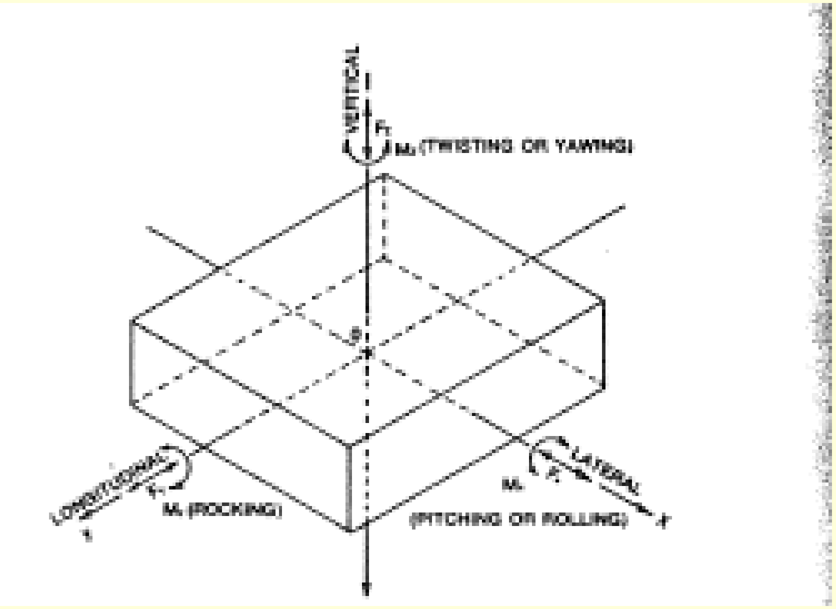


Figure 28: Modes of vibration of machine which are transferred to the piles supporting the foundation

Researchers Novak, Donavan, Stevens, Indrajit Chowdhury, etc proposed simple but reliable solutions for the analysis of piles/pile groups subjected to dynamic loading.

Several researchers also proposed more complex and rigorous solutions using FEM techniques.

Earthquake loading on piles.

Earthquake loading is catastrophic for the pile foundation due to the fact that it induces very high lateral loading from the surrounding soil and the superstructure it carries causing a flexural failure of the pile due to its slenderness. Hence, this calls for a rigorous study of pile response to earthquake loading using complex mathematical/computational methods

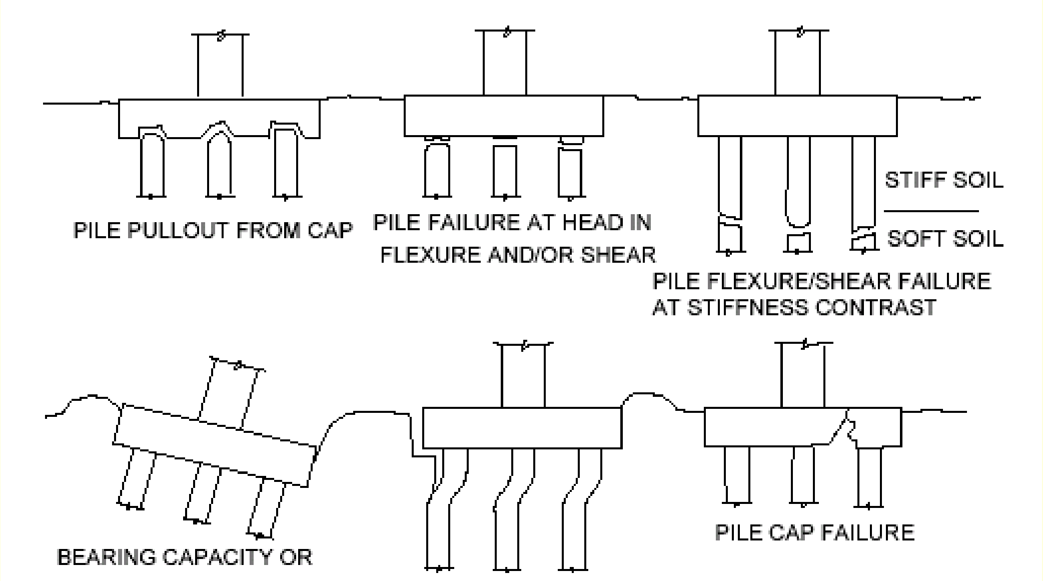

PILE PULLOUT FROM CAP
PILE FAILURE AT HEAD IN FLEXURE AND/OR SHEAR
STIFF SOIL
SOFT SOIL
PILE FLEXURE/SHEAR FAILURE AT STIFFNESS CONTRAST
BEARING CAPACITY OR TENSION PULL-OUT FAILURE
EXCESSIVE LATERAL DEFORMATIONS
PILE CAP FAILURE

Figure 29: Potential failure modes of pile foundations subjected to seismic loading

3.PILE INSTALLATION

Pile installation is as important as design. In this section, two types of methods:

a)Installation by Driving
b)Installation by Boring

Are presented in the subsequent slides

Before going through pile installation methods understand the following terminology.

Driven pre-cast pile: The pile is casted in a yard brought to the site and driven by some mechanism into the soil

Driven Cast-in-situ pile: A casing plugged at bottom is driven into the ground and then the pile is casted by removing or retaining the casing

Bored Pre-cast pile: A bore is made and the soil inside is removed and then a pile casted in some yard is put into the bore

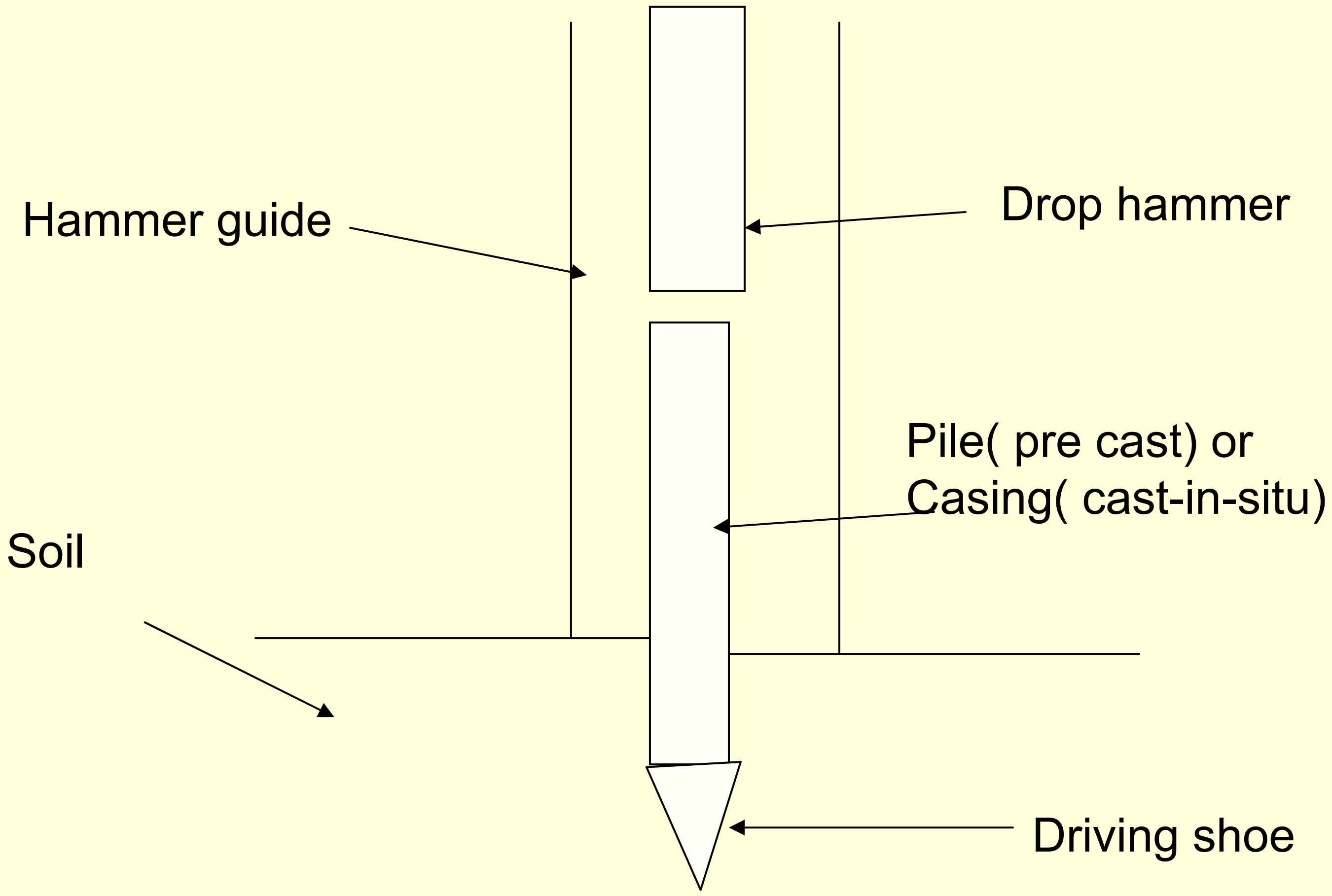
Bored Cast -in-situ pile: A bore is made the soil is removed and the pile is casted at site in the bore.

Installation by Driving

- If the driving has to be carried out by hammer, the following factors should be take into consideration.

- The size and weight of the pile
- The driving resistance which has to be overcome to achieve the desired penetration
- The available space and head room in the site (because the hammer has to be dropped from certain height and also the initial height is approximately height of the pile + height of fall of the hammer)
- The availability of cranes
- The noise restrictions which may be in force in the locality

Schematics of pile driving with hammer



Hammer guide

Drop hammer

Pile(pre cast) or
Casing(cast-in-situ)

Soil

Driving shoe

Figure 30

Methods of pile driving

- Dropping weight
- Explosion
- Vibration
- Jacking (only for micro piles)
- Jetting

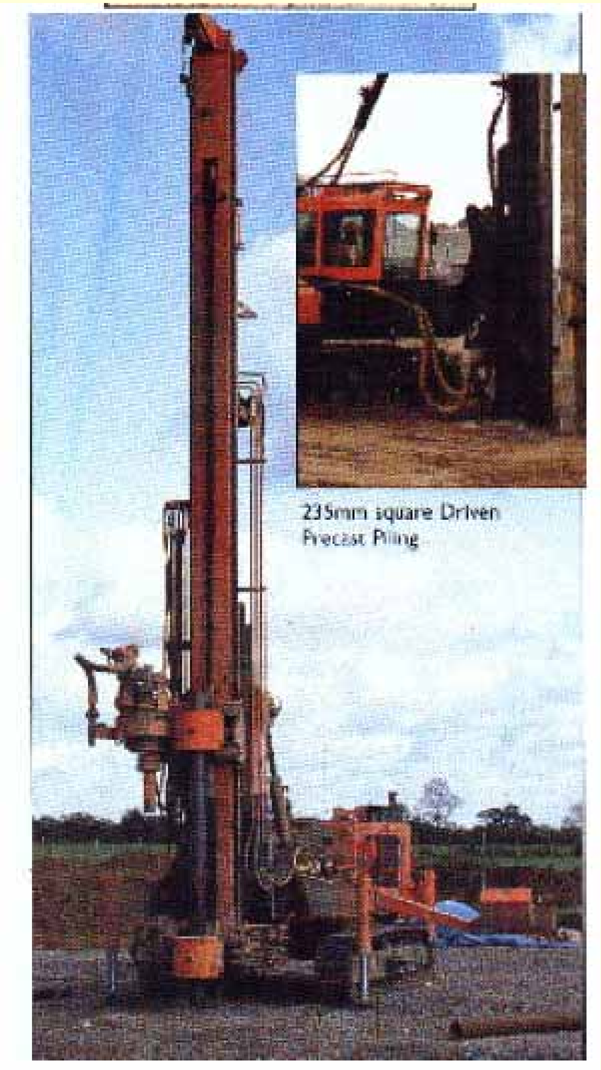


Figure 31: Hammer driven pile-real time

Installation by Boring

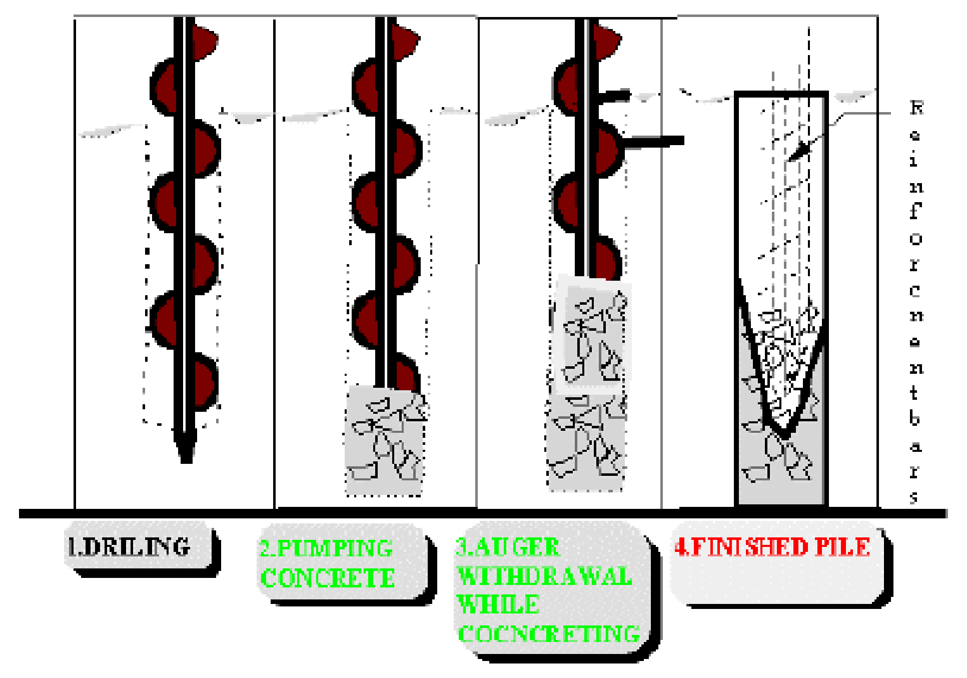


Figure 32 : Installation by mechanical auger schematics

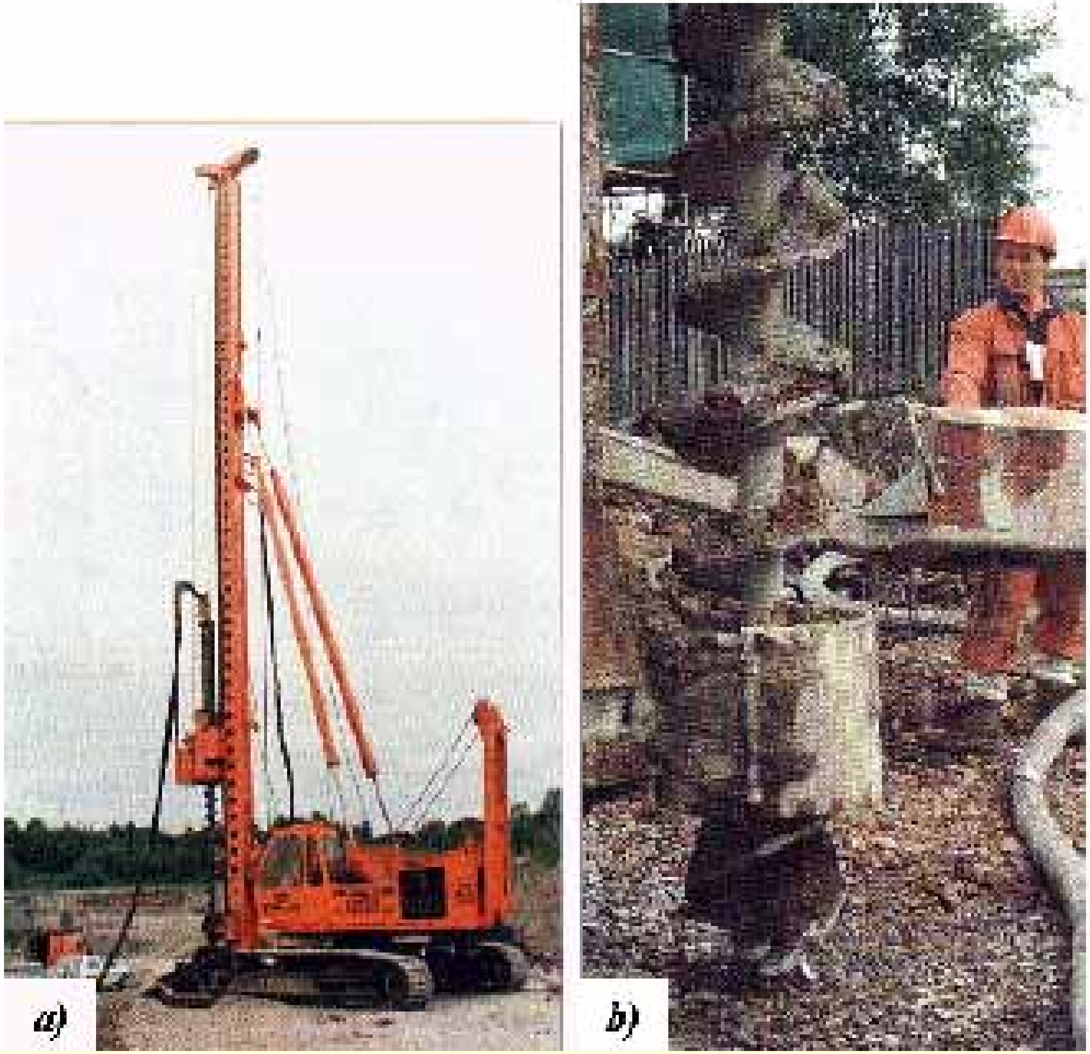
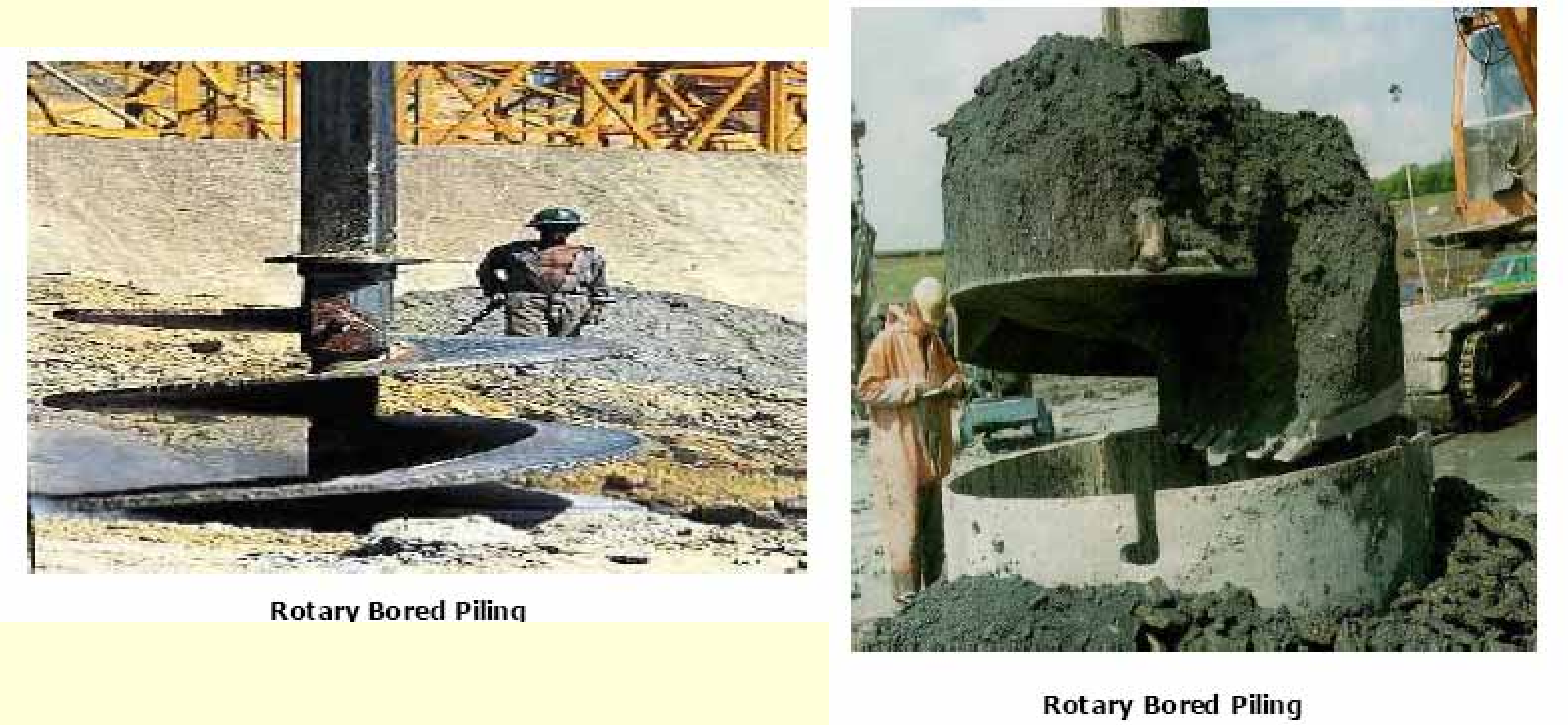


Figure 33: Mechanical Auger-real time

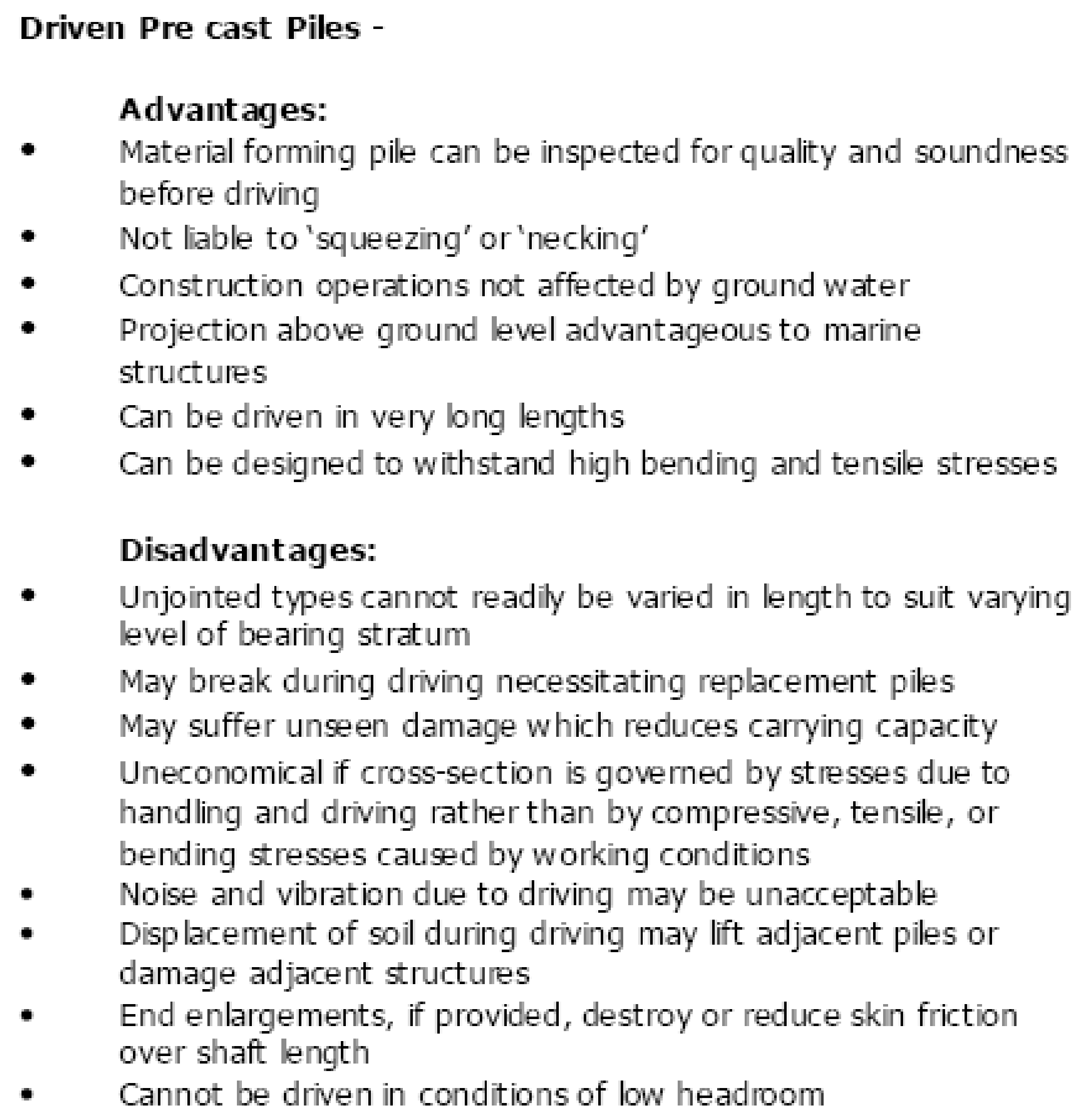


Rotary Bored Piling

Rotary Bored Piling

Figure 34: Rotary Bored Piling- real time

Advantages and Disadvantages of various piles



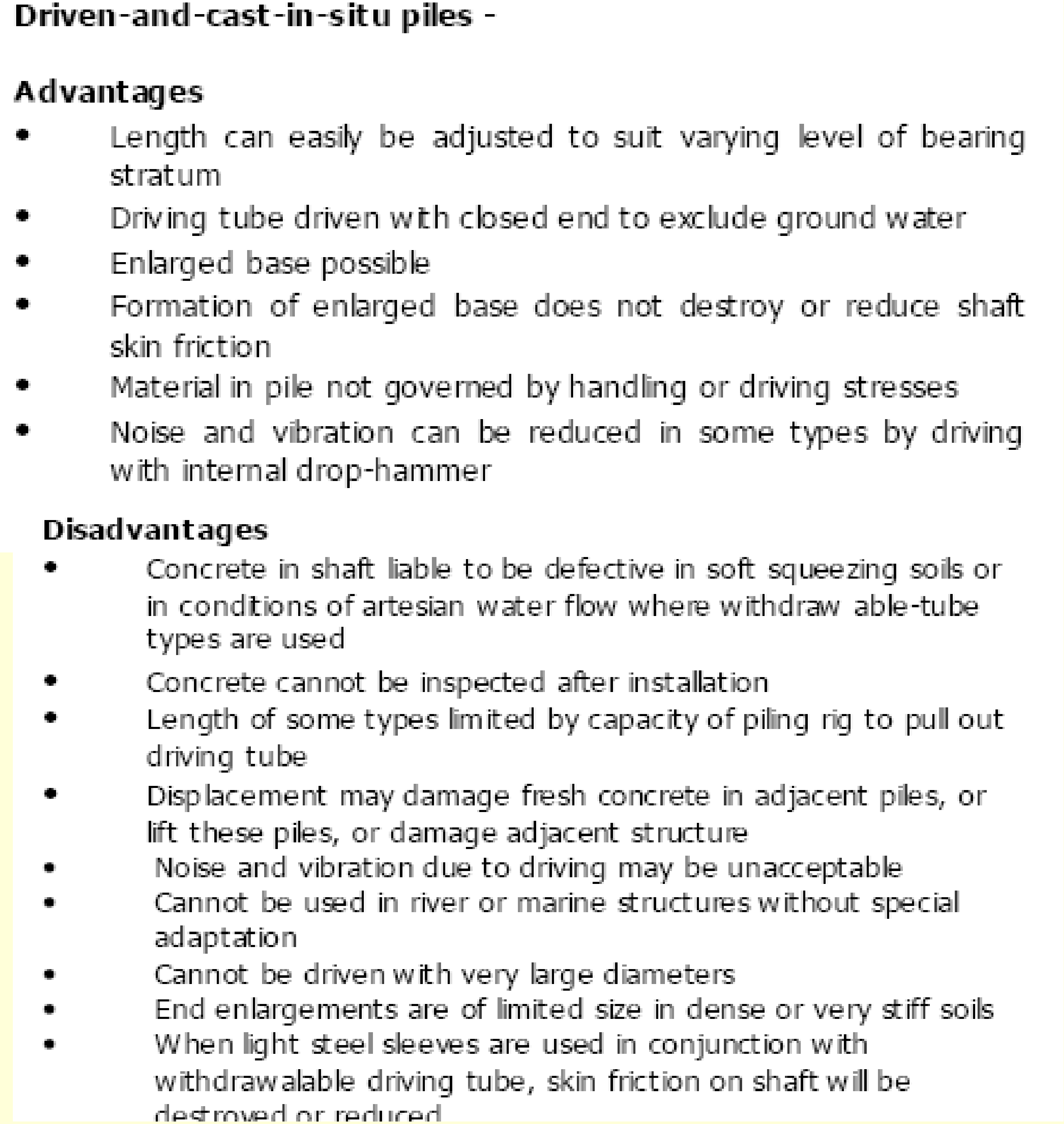
Driven Pre cast Piles -

Advantages:

- Material forming pile can be inspected for quality and soundness before driving
- Not liable to 'squeezing' or 'necking'
- Construction operations not affected by ground water
- Projection above ground level advantageous to marine structures
- Can be driven in very long lengths
- Can be designed to withstand high bending and tensile stresses

Disadvantages:

- Unjointed types cannot readily be varied in length to suit varying level of bearing stratum
- May break during driving necessitating replacement piles
- May suffer unseen damage which reduces carrying capacity
- Uneconomical if cross-section is governed by stresses due to handling and driving rather than by compressive, tensile, or bending stresses caused by working conditions
- Noise and vibration due to driving may be unacceptable
- Displacement of soil during driving may lift adjacent piles or damage adjacent structures
- End enlargements, if provided, destroy or reduce skin friction over shaft length
- Cannot be driven in conditions of low headroom



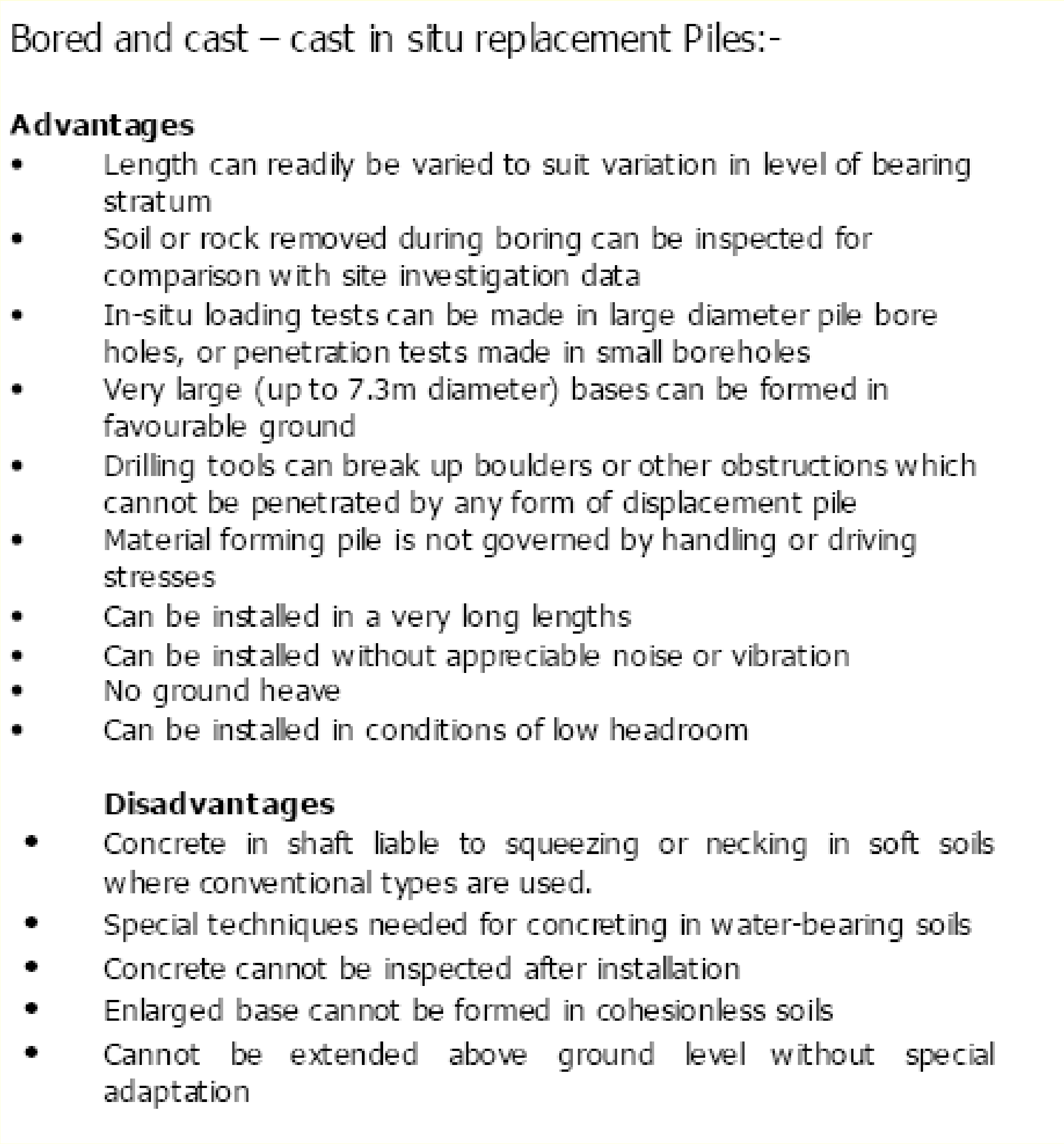
Driven-and-cast-in-situ piles -

Advantages

- Length can easily be adjusted to suit varying level of bearing stratum
- Driving tube driven with closed end to exclude ground water
- Enlarged base possible
- Formation of enlarged base does not destroy or reduce shaft skin friction
- Material in pile not governed by handling or driving stresses
- Noise and vibration can be reduced in some types by driving with internal drop-hammer

Disadvantages

- Concrete in shaft liable to be defective in soft squeezing soils or in conditions of artesian water flow where withdraw able-tube types are used
- Concrete cannot be inspected after installation
- Length of some types limited by capacity of piling rig to pull out driving tube
- Displacement may damage fresh concrete in adjacent piles, or lift these piles, or damage adjacent structure
- Noise and vibration due to driving may be unacceptable
- Cannot be used in river or marine structures without special adaptation
- Cannot be driven with very large diameters
- End enlargements are of limited size in dense or very stiff soils
- When light steel sleeves are used in conjunction with withdrawalable driving tube, skin friction on shaft will be destroyed or reduced



Bored and cast – cast in situ replacement Piles:-

Advantages

- Length can readily be varied to suit variation in level of bearing stratum
- Soil or rock removed during boring can be inspected for comparison with site investigation data
- In-situ loading tests can be made in large diameter pile bore holes, or penetration tests made in small boreholes
- Very large (up to 7.3m diameter) bases can be formed in favourable ground
- Drilling tools can break up boulders or other obstructions which cannot be penetrated by any form of displacement pile
- Material forming pile is not governed by handling or driving stresses
- Can be installed in a very long lengths
- Can be installed without appreciable noise or vibration
- No ground heave
- Can be installed in conditions of low headroom

Disadvantages

- Concrete in shaft liable to squeezing or necking in soft soils where conventional types are used.
- Special techniques needed for concreting in water-bearing soils
- Concrete cannot be inspected after installation
- Enlarged base cannot be formed in cohesionless soils
- Cannot be extended above ground level without special adaptation

4.MISCELLANEOUS

Pile driving formulae

To develop the desired load carrying capacity, a point bearing driven pile must penetrate sufficiently into a dense soil layer or have sufficient contact with a layer of rock. This requirement cannot always be satisfied by driving a pile to a pre-determined depth, because soil profiles vary. For that reason several formulae have been developed to calculate the ultimate capacity of the pile during driving. They are based on Energy Approach and are independent of the soil into which pile is driven. Some of the formulae are given below. The reader is requested to go through literature suggested in references at the end. The famous of these formulae is Engineer’s news (EN) record formula. The modified form of this formula is presented below

$$Q_u = (E\,W_R\,h)*(W_R + n^2 W_P) / (S+C)*(W_R + W_P)$$

Contd. Next Slide

Where,

Q_u = Ultimate capacity of the pile

W_R = Weight of the ram

h= height of fall of the ram

W_p= Weight of the pile

C= a constant

S=Penetration of pile per hammer blow

n= Coefficient of restitution between ram and pile cap

E= Efficiency of the hammer

Pile cap configurations

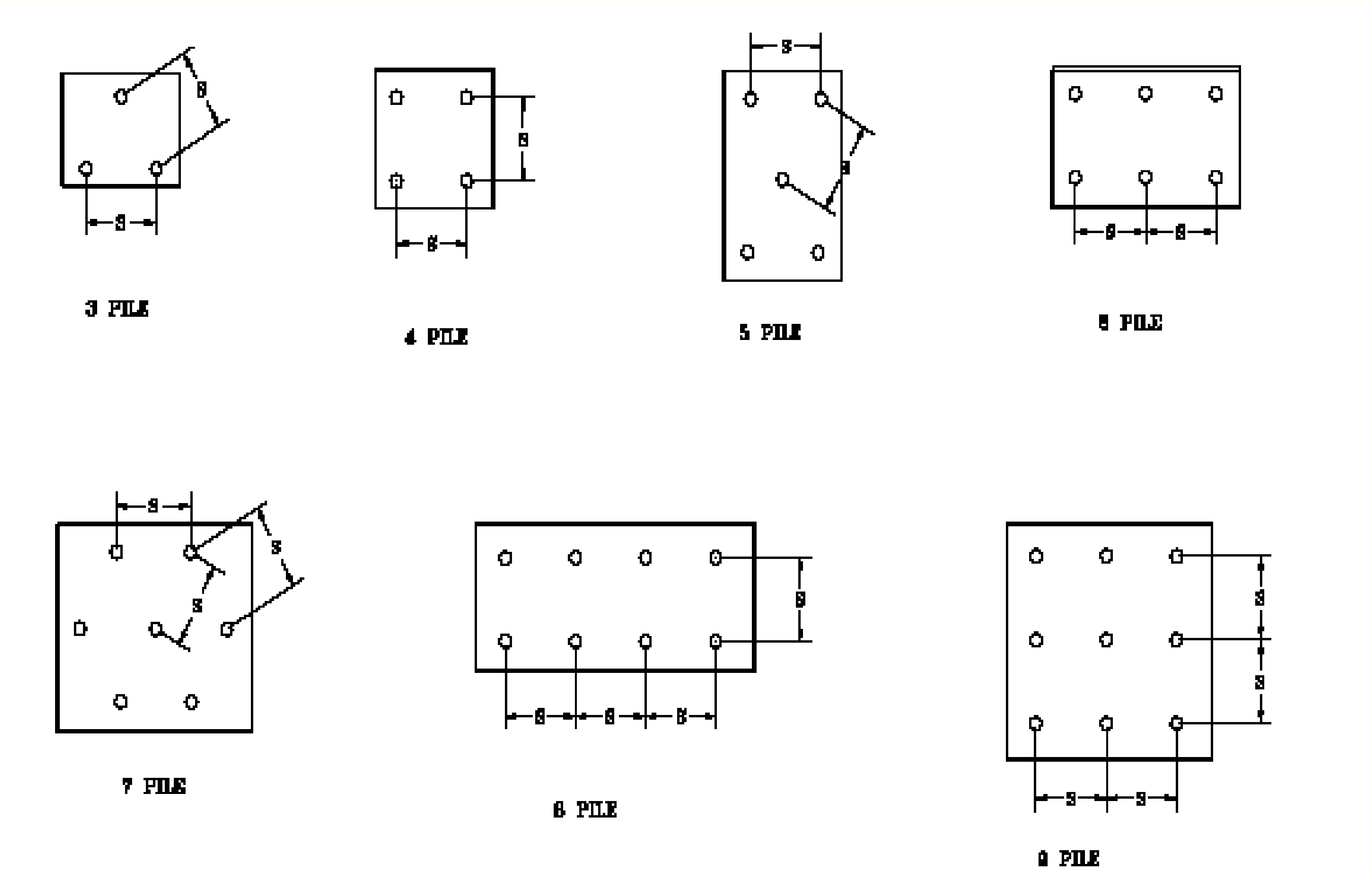
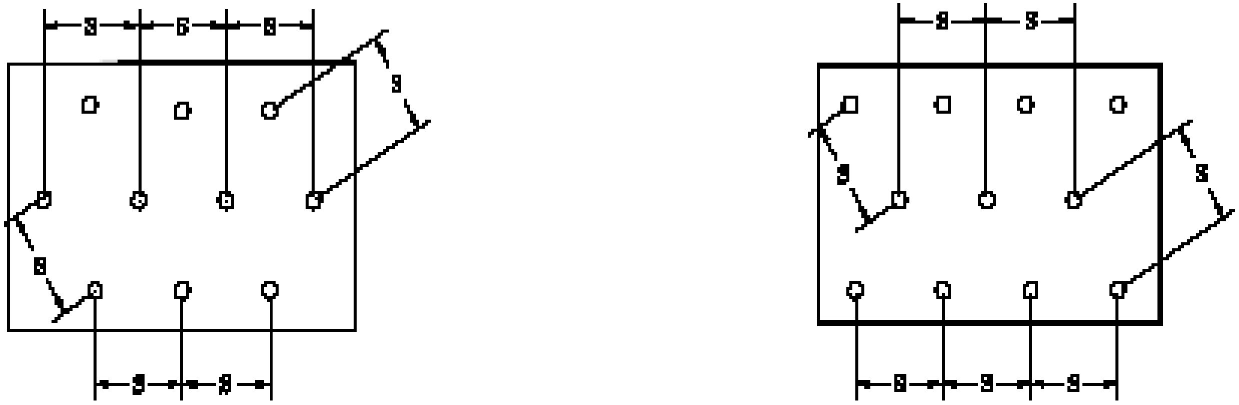
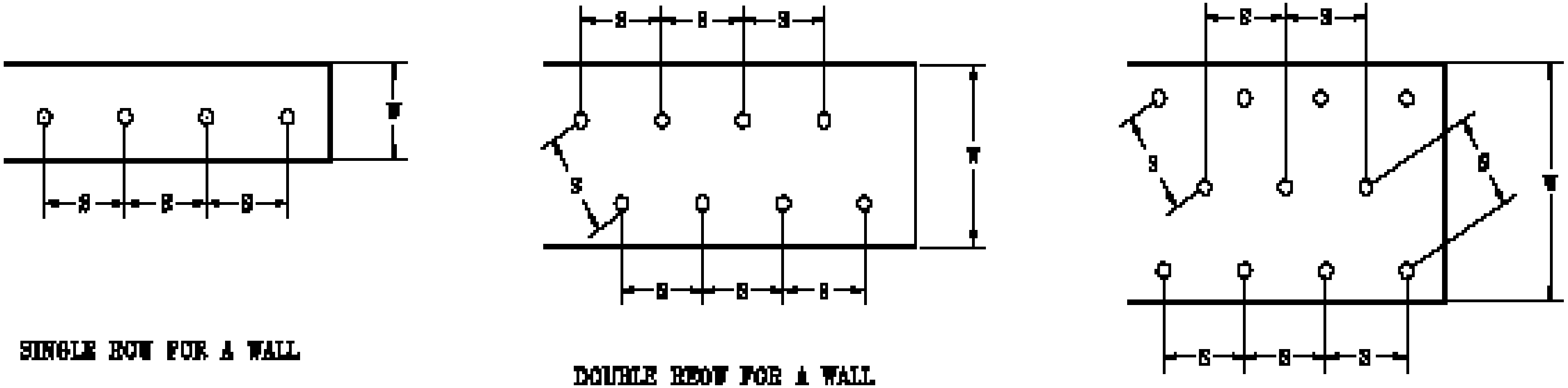


Figure 35



10 PILE

11 PILE



SINGLE ROW FOR A WALL

DOUBLE ROW FOR A WALL

TRIPLE ROW FOR A WALL

Figure 36

Structural Design of Pile and Pile cap

Structurally the pile section is designed as column for

- **Compression plus Bending**

- **Tension plus bending**

The pile cap is designed as rigid or flexible.

- **A rigid (very high flexural strength between two adjacent piles) pile cap is designed for one way shear and punching shear.**

- **A flexible (average flexural strength between piles) pile cap is analyzed by FEM by considering the piles as vertical springs and then designed for the stresses obtained from the analysis**

Flow chart for pile selection

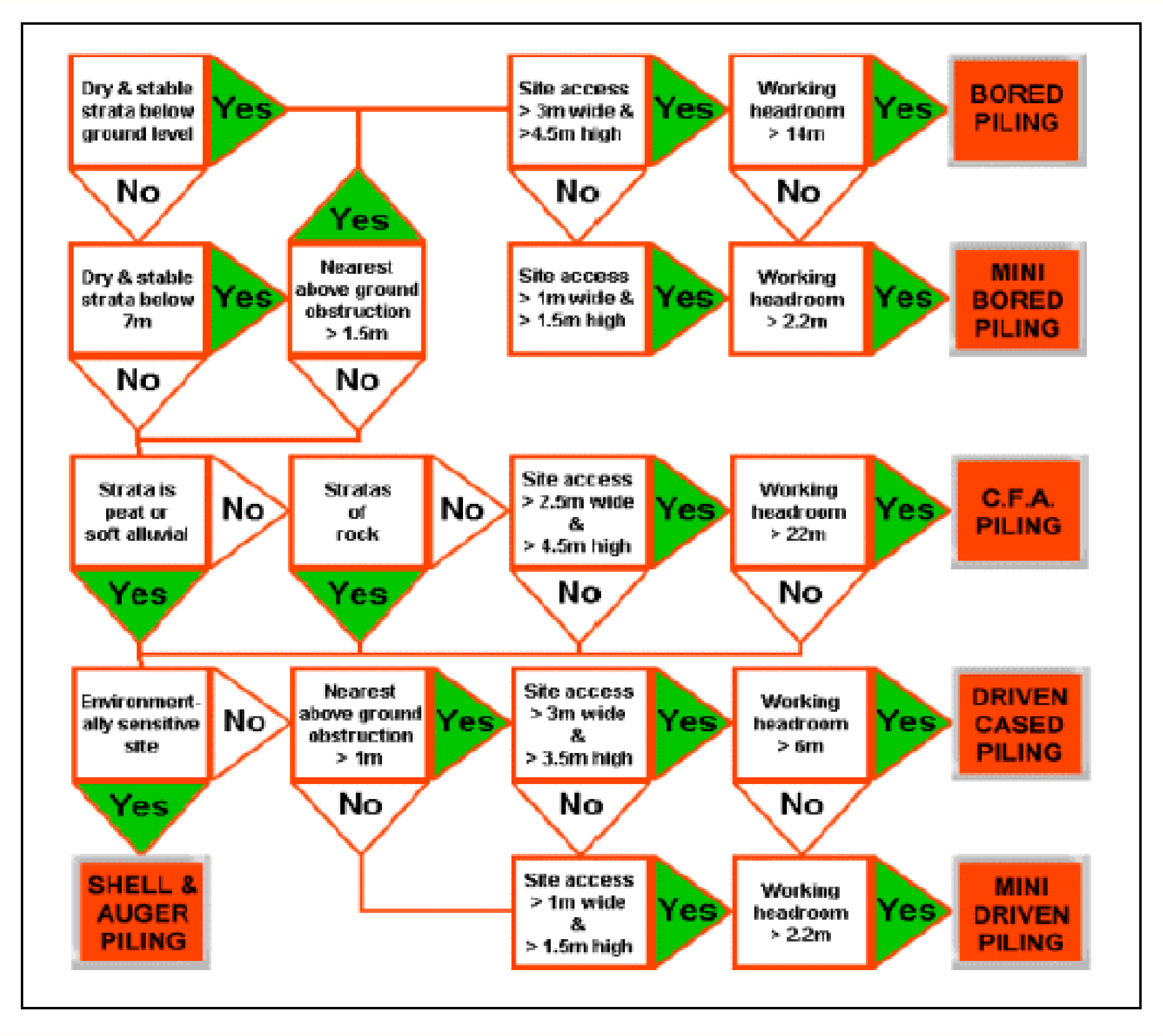

Dry & stable strata below ground level
Yes
No
Site access > 3m wide & >4.5m high
Yes
No
Working headroom > 14m
Yes
No
BORED PILING
Dry & stable strata below 7m
Yes
No
Yes
Nearest above ground obstruction > 1.5m
No
Site access > 1m wide & > 1.5m high
Yes
Working headroom > 2.2m
Yes
MINI BORED PILING
Strata is peat or soft alluvial
No
Yes
Stratas of rock
No
Yes
Site access > 2.5m wide & > 4.5m high
Yes
No
Working headroom > 22m
Yes
No
C.F.A. PILING
Environment-ally sensitive site
No
Yes
SHELL & AUGER PILING
Nearest above ground obstruction > 1m
Yes
No
Site access > 3m wide & > 3.5m high
Yes
No
Working headroom > 6m
Yes
No
DRIVEN CASED PILING
Site access > 1m wide & > 1.5m high
Yes
Working headroom > 2.2m
Yes
MINI DRIVEN PILING

Figure 37

Real time Pictures of Piles

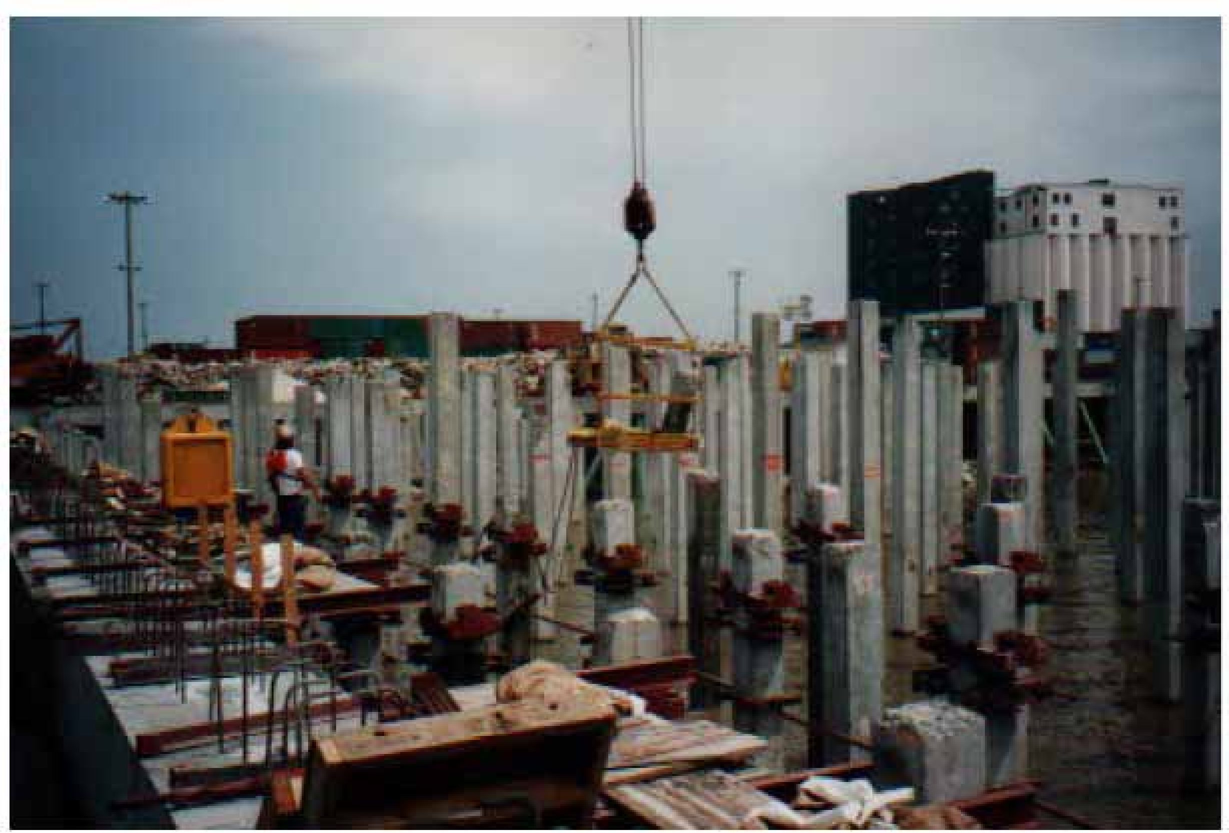


Figure 38

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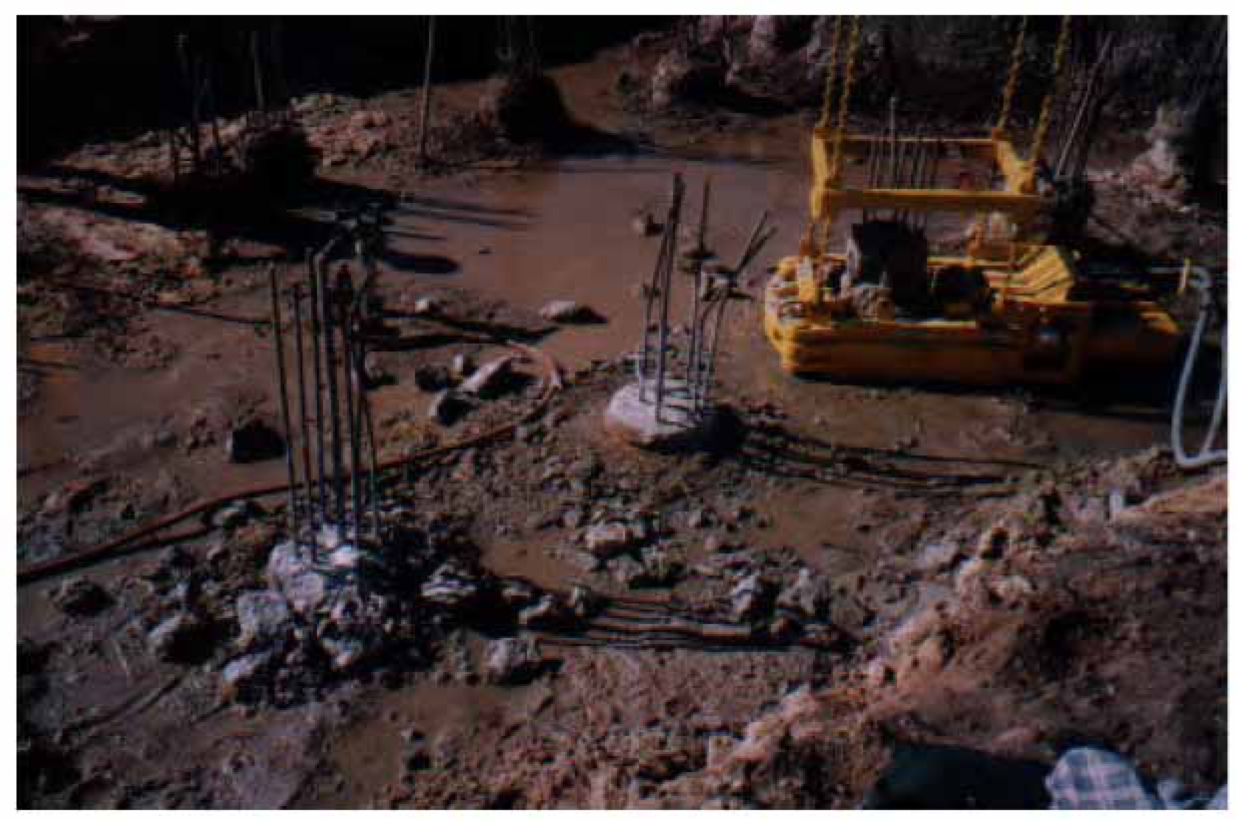

Figure 39

04/03/2009

5.References

Please refer the below books for detailed info on pile foundations.

For purpose of industrial practice:

- Principles of Foundation Engineering by B.M.Das
- Foundation Analysis and Design by Joseph. E.Bowels
- Foundation Design Manual for Practicing Engineers by Narayan.V.Naik
- Foundation Design by Wayne.C.Teng

For advanced information on the subject:

- Pile foundation Analysis and Design by Poulus.H.G. and E.H.Davis
- Foundation Design and Construction by Tomlinson.M.J.
- Deep foundations by United Facility Criteria (UFC) – US Army

Thank You